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**AUGMENTED VISIBILITY IN ARCHITECTURAL SPACE:
INFLUENCING MOVEMENT PATTERNS**

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Submitted 19th July 2013

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Abstract

The rapid development of computing associated with our modern era has resulted in exciting and innovative incorporation of digital technology in architectural design. However, this presents challenges for established theories of spatial analysis, such as space syntax, developed by Hillier and Hanson.

The research presented in this thesis identifies and addresses a lack of knowledge concerning the impact of digitally manipulating physical architectural environments by introducing perceived visual depth into them. The research contributes to the development of space syntax theory by showing that the introduction of perceived visual depth in architectural space impacts on people's behaviour, and that space syntax theory needs to be adjusted to account for this phenomenon.

The overarching hypothesis of the experiments detailed by the thesis was that ambient displays can be introduced into physical architectural settings to augment the perceived visual depth of a space by virtually linking and extending physical space towards another real or virtual space. This augments the topological and visual relations of a space which influences how people use and move within such settings.

To investigate the hypothesis a series of experiments was designed and conducted. A pilot study showed that manipulating the perceived depth of a wall through digital projection had a significant effect on people's use of the space.

The first of the main experiments showed that the position of an ambient display, acting as a virtual window through the wall upon which it was placed, had the capacity to influence people's behaviour in space. This was established by designing a T-shaped corridor which participants entered from the bottom and were therefore required to make a left or right-hand turn decision to access a target area beyond the corridor. Whilst the environment was held constant the display was placed in one of three conditions, central, left, or right. The analysis showed that people's turn-based decisions were affected by the position of the display.

The second experiment used the same architectural setting but held the position of the ambient display constant in the central position whilst altering what it displayed in three conditions. The display either acted as a realistic virtual window, showing what would be seen if the display was a real window or it skewed the perspective of the image by manipulating the vanishing point towards the left or right. The turn-based decisions of participants entering the corridor were recorded and the results showed that they were significantly influenced by the manipulation.

The experimental data showed that digital displays can act as virtual windows which alter spatial relations in a simple architectural space. This knowledge, combined with an awareness that current methods of spatial analysis cannot account for the impact of introducing digital depth into architectural space, show that theories must be adapted to ensure their ability to model behaviour in hybrid architectural environments which incorporate digital technology.

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CHAPTER 1 - INTRODUCTION

1.1 Background

1.2 Aim and Scope

1.3 Research Hypotheses

1.4 Methodology

1.5 Overview of Thesis

Chapter 1 - Introduction

1.1 Background

Humans have a long history of augmenting their surroundings, both to beautify them and convey important information to their societies. This can be seen in the rudimentary style of prehistoric cave paintings or in the sophisticated frescos of the Renaissance period. Very recently, advances in technology have introduced new and exciting ways in which this historic form of manipulation can be achieved. Architects and designers are no longer limited to static design but can employ innovative new technology to create dynamic and fully adaptive architectural space, where buildings can interact with their users.

As technology develops the boundaries between physical and virtual space are dissolving. Pervasive computing is radically changing the relationships individuals have with constructed environments (Mitchell, 2003). Recently, Google's public launch of 'Google Glasses', an augmented reality wearable computer developed by Project Glass R&D project, raised public awareness of the potential scope of augmented reality, however, less high profile examples of pervasive computing are becoming more common in people's everyday environments and commercial organisations are investing. For example, in 2013 a voice-activated shop window display created by 'Knit', a marketing agency, promoted Samsung's 'Smart TVs', and

in late 2012 Sony and 'Naked Communications' developed an innovative promotion for Sony products through the, 'Headphone Music Festival', by using original augmented reality performances from four local rock bands in Shibuya, Tokyo which could be activated by scanning a typical looking band poster with a mobile phone.

1.2 Aim and Scope

The thesis identifies and addresses a lack of research concerning the impact of digitally manipulating physical architectural environments by introducing perceived visual depth into them. The research contributes to the development of space syntax theory, first developed by Hillier and Hanson (1984), by showing that the introduction of perceived visual depth in architectural space impacts on people's behaviour, and that space syntax theory needs to be adjusted to account for this phenomenon.

'Researchers should consider using space syntax when their research requires that they describe with precision how spatial environments enable or impede users' behaviours. Their research can contribute to the development of space syntax by making it increasingly sensitive to the spatial properties of the environment under investigation'. (Peponis, 2002, p4.)

Current research into the integration of ambient technology into architectural space tends to focus on the interaction between humans and computers without considering the environment as the third key component which hosts both people and technology. Despite the fact that there is some research investigating pervasive systems in urban environments, this tends to focus on social behaviour and does not

consider the influence of ambient displays on human movement (Fatah gen. Schieck et al., 2005; 2007).

Drawing from this finding, by showing how integrated digital technology can affect the perceived spatial boundaries of physical architectural space the experimental research presented in this thesis will highlight the need for spatial analysis techniques which can account for these new environments.

The overarching hypothesis of the work is that ambient displays can be introduced into physical architectural settings to augment the perceived visual depth of a space by virtually linking and extending physical space towards another real or virtual space. This augments the topological and visual relations of a space which influences how people use and move within such settings. Underpinning this hypothesis is a theoretical assumption that the topological and visual relations between physical spaces are two important factors that determine the distribution of people's movement in space (Hillier, 2004).

The research draws upon existing theories of space cognition current methods for spatial analysis and studies concerning the nature of the relationship between human and ambient displays.

By studying and understanding behaviour in conditions where ambient displays are embedded in architectural space, this thesis is able to offer important knowledge to architects who are increasingly working within worlds where fusion between virtual and physical architectural space is prevalent (Spiller, 2002). The investigation of

movement in digitally augmented architectural spaces has the capacity to provide a better understanding of the relationship between humans, space and ambient displays as a digital extension of space.

1.3 Research Hypotheses

Hypothesis 1

Ambient displays can be introduced into physical architectural settings to augment the perceived visual depth of a space by virtually linking and extending physical space towards another real or virtual space. This augments the topological and visual relations of a space which influences how people use and move within such settings.

A testable statement was developed for the preliminary investigation of the hypothesis carried out in the pilot study and is presented below:

Pilot study hypothesis:

Digitally augmenting the perceived physical depth of a wall in a simple architectural setting will change people's use of the space.

Combining the knowledge from the literature review and the pilot study two further hypotheses were generated for the main experimental testing phase.

Experiment 1 hypothesis

The location of a digital display, which augments physical space by introducing augmented depth information, will influence how people move through a T-shaped corridor.

Experiment 2 hypothesis

A display placed centrally in a T-shaped corridor, providing a skewed (either left or right) perspective projection of the space beyond the wall, will influence people's turn-based decisions at the junction of the T-shaped corridor.

1.4 Methodology

To test the overarching hypotheses of the research an experimental approach was adopted. This provided an opportunity to conduct controllable and replicable research that was able to identify the influence of augmented visual depth on people's movement in a setting which closely emulated a natural environment.

A series of experiments were developed to analyse the changes in people's movement patterns in experimental settings when ambient displays are used as a virtual extension of physical architectural space and thus as a digital extension of the visual boundaries.

An initial pilot study provided a test-bed with which to explore the observable effects of the introduction of digitally augmented depth in a simple architectural setting.

Using the knowledge gained from the pilot study more sophisticated experiments were developed in the main testing phase with which to assess the capacity of digital depth augmentation to influence navigation decisions made in architectural settings. This was carried out by using ambient displays to create virtual windows in an experimental space designed as a T-junction where participants were required to make a left or right-turn decision to access a target area beyond the experimental space.

1.5 Overview of Thesis

Chapter 2 sets out a literature review which focuses on the relationships between visual perception, ambient technology and architectural space. This identifies key gaps in the knowledge to be addressed by the thesis. The review can be considered as two distinct sections, the first of which provides an overview of perception and space cognition literature and the second which provides a review of ambient technology and its integration in architectural space. The chapter concludes with a summary of the identified knowledge gaps.

Chapter 3 sets out the methodological approach of the research and details the experimental hypotheses tested by the research. The chapter presents a rationale for the choice of the methodology and an overview of the experimental design of the studies presented in Chapters 4 and 5.

Chapter 4 details the pilot study which challenges the perception of boundaries in a hybrid system. This was tested by the introduction and manipulation of digitally

augmented depth in a simple architectural space and the measurement of people's use of the space under the different conditions.

Chapter 5 details the two main experiments. The experiments build on the knowledge gained from the pilot study and introduce a measurable outcome of a 'left' or 'right' turn-based decision made by participants entering the experimental space which was designed as a T-junction corridor which provided access to a target area beyond the corridor. The turn-based decision was the only measurable outcome of the experiments. Experiment one tested how the location of digital displays acting as 'digital windows' affect the navigation decision of participants. Experiment two explored the effect of skewing the perspective of a centrally placed 'digital window' on the turn-based decision of participants.

Chapter 6 provides the discussion and conclusion to the thesis, providing a summary of the outcomes from the experiments in response to the aims of the work. It also details the significant contribution of the thesis and the implications this has. Criticisms of the research are presented with recommendations for improvements. The thesis concludes with suggestions for future research directions.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

2.2 Visual Perception of Space

2.3 Spatial Analysis of
Architectural Space

2.4 Ambient technology

2.5 Ambient displays in
architecture

2.6 Conclusion

Chapter 2 - Literature Review

2.1 Introduction

The research presented by this thesis explores the potential impact of visual depth augmentation, through the use of ambient displays, on the movement of people through architectural space. In order to understand the fundamental principles of the topic being studied the literature review examines research into the relationships between human perception, visual ambient technology and architectural space.

The review can be considered as comprised of two sections:

The first section provides an overview of perception and space cognition literature with a focus on the importance of perception in people's navigation of space. In addition, the section also reviews current theories of spatial and visibility analysis through which the relationships between architectural space, perception and human behaviour can be understood.

The second section provides an introduction to ambient technology and the relationships between perception of physical space and digital information (virtual space). The section reviews literature which concerning the integration of ambient displays in architectural space as well as potential future developments in the field. It also makes reference to human-computer interaction and how ambient technology

penetrates into people's lives, considering the concept of ubiquitous computing and how ambient technology can be used to influence behaviour and promote social engagement.

2.2 Visual Perception of Space

2.2.1 History of Perception Research

Understanding visual perception is fundamentally important when investigating people's movement through architectural space.

Human enquiry into the nature of visual perception has a long history which can be traced back to scholars in ancient Greece. In a tradition long repeated by scholars through the ages two opposing and incompatible theories were developed. These can be broadly classified as either 'intromission' or 'extramission' theories.

Intromission theories suggested that perception comes about through a representation of an object entering the eyes. In the fifth century B.C., Democritus (c.a. 460 B.C. – 370 B.C.) postulated that objects contained multiple replicas of themselves each called an eidolon. According to the theory, objects continually emit eidola and it is these that reach and enter a person's eyes in a process where the air between the object and perceiving eye is 'contracted and stamped' creating 'pressed' air which held properties of the object which moved and thus 'appears in the eye' (Putri, 2007, p.1).

Epicurus (ca. 341 B.C – 270 B.C.) postulated that particles from objects continuously flowed into the observer's eye but diverged from Democritus' belief in pressed air, suggesting instead that the perceiver's eye was directly impacted by 'husks' emanating from the object:

'Sight and perception are due to images received directly from the surfaces of objects. We would not perceive their shape or colour very effectively if their emanations were actively mediated by the intervening air [as Democritus believed], or by means of light-rays or some sort of flowing current directed to us by them. Rather, we are directly impacted by husks from the objects, which share the colour and shape of their source, but are thin enough to penetrate our senses.'

Epicurus, Letter to Herodotus (translated by Anderson, 2006)

In contrast, extramission theories contended that perception occurs through rays of light which are emitted by eyes and then, having encountered objects, return with information about objects. The development of this theory is associated with Euclid (ca. 325 B.C. - 265 B.C.), whose focus was to understand visual perspective and who developed a set of postulates with which to explain how the size, position and clarity of an object was perceived.

Ptolemy (ca. 100 – 175) was a follower of Euclid and extended extramission theory incorporating philosophical, physiological and mathematical thinking. In the text, *Optics*, Ptolemy made the earliest recorded attempts at measuring refraction of light between media with different densities (Ross and Ross, 1976). In addition, Ptolemy

also posited that the properties of the emitted visual ray were the same as external light and that the rays of Euclid's theory were a representation of the geometry of vision but not the reality (Putri, 2007).

Ibn al-Haytham (965-1040), was influenced by Ptolemy's thinking. However, his body of work, whilst finding both intromission and extramission theories inaccurate, was more closely aligned with intromission theory. Ibn al-Haytham, was a polymath sometimes referred to as 'the father of modern optics' in reference to his influential text entitled, 'Book of Optics'. This detailed research which employed scientific method in his investigation of optics and found evidence to suggest that perception came about through rays of light proceeding to the eye from each point of an object. Ibn al-Haytham's theory and methods of investigation formed the foundation for modern investigation.

Working in the early 17th Century, Johannes Kelper was the first scholar to describe the formation of the retinal image. It is the discovery and understanding of this two dimensional image which raised questions about how we can see in three dimensions. This problem, which is fundamental to the topic of this thesis, has been the subject of extensive investigation by modern academics.

2.2.2 Constructivist Theories of Vision

Hermann von Helmholtz developed the foundation for the constructivist theory of vision having studied the anatomy of the human eye and concluded that it was not optically powerful enough to provide the information required for vision (von Helmholtz, 1866). Therefore, Helmholtz argued that unconscious inferences were an intrinsic part of perception. That is, due to the poverty of information in the retinal image people do not perceive the world directly but interpret data in order to construct their perception: a person's knowledge, expectations *and* the visual stimulus itself are involved in the perceptual process. Gregory (1970) developed von Helmholtz's theory into his constructivist, or 'top-down' theory. According to this, 'top down' processing is required for perception using contextual information to aid pattern recognition. The theory argues that perception requires a person to make inferences about what they see and therefore, their prior knowledge and experiences are crucial for the success of the process. Gregory suggested that in most cases, these hypotheses were correct, but incorrect hypotheses lead to mistakes in perception, as shown when viewing visual illusions, such as the visually ambiguous Necker Cube which can be perceived in two different ways without any alteration of sensory input. Gregory argued that this illusion supported his theory that perception is a top down process because it is possible for an environmental input to remain constant and for the brain to form two equally valid hypotheses about the data and perceive the image differently. However, visual illusions can also be used to demonstrate weaknesses in Gregory's theory. Given that there is a direct

relationship between a hypothesis and perception it should be expected that by altering a hypothesis, through learning about a visual stimulus, that mistakes in perception can be corrected. However, it has been shown that some illusions persist despite learning, for example, Gregory's inverted face (Gregory, 1974).

2.2.3 Gibson's Ecological Theory

In strong contrast to the cognitive model proposed by Gregory, Gibson (1966) developed the 'ecological' theory of perception which proposed that perception did not arise through inference and interpretation but was direct; the information required for perception is available in the environment.

Gibson's ecological approach differs from preceding theories in two respects, firstly, that perception is an achievement of perceiver-environment systems, rather than the achievement of an individual's brain, and secondly, that the primary function of perception is the guidance and adjustment of behaviour in an environment rather than just representation.

Gibson championed the idea of perception as an active process requiring action by the perceiver, for example, scanning the environment to identify the target object. The active process guides behaviour which in turn stimulates even more activity, for example once the perceiver has identified the target object in the environment they may decide whether to touch it or not. *'They do not observe the environment just with their eyes, but with the eyes of their mobile body'* (Gibson, 1979, p. 222). Active perception considers the possibilities of the environment as the motivator for action.

Gibson's theory of visual perception has three key concepts:

- Optic array – The visual information received by the retina, which provides unambiguous perceptual information.
- Textured gradients – Textured gradients are perceived through the flow of optic array as the perceiver moves. They provide information about distance and speed.
- Affordance – The attachment of meaning to visual information. Gibson suggested that the use of an object is directly perceivable, for example, a door knob 'affords' turning it round or an open environment affords free movement whilst a spatially defined environment affords prescribed directed movement. Dourish (2004) described affordances as, 'a property of the space that affords action to appropriately equipped organisms' (p. 118).

2.2.4 Extending Gibson's theory

Norman (1988) extended the meaning of affordances and explored the relationships between form and function in the design of cognitive artefacts in order to demonstrate that good design makes the use of an object clear and obvious to the user. Moreover, the different possibilities can act as affordances to which people within space are drawn.

Bloomer and Moore (1977) also placed the human body at the centre of our understanding of architectural form. By having the body as the central reference

point for perception, people interpret spatial qualities in relation to their bodies. According to Merleau-Ponty (2002) body and space are inter-related and movement can be the medium for exploring and defining this relation. In one respect, the placement of specific architectural components can prompt somebody to move, change direction or even increase their social interaction and in another, movement itself can be used as a basis for understanding properties of space and how they may influence social interaction.

2.3 Spatial Analysis of Architectural Space

2.3.1 The Development of Space Syntax

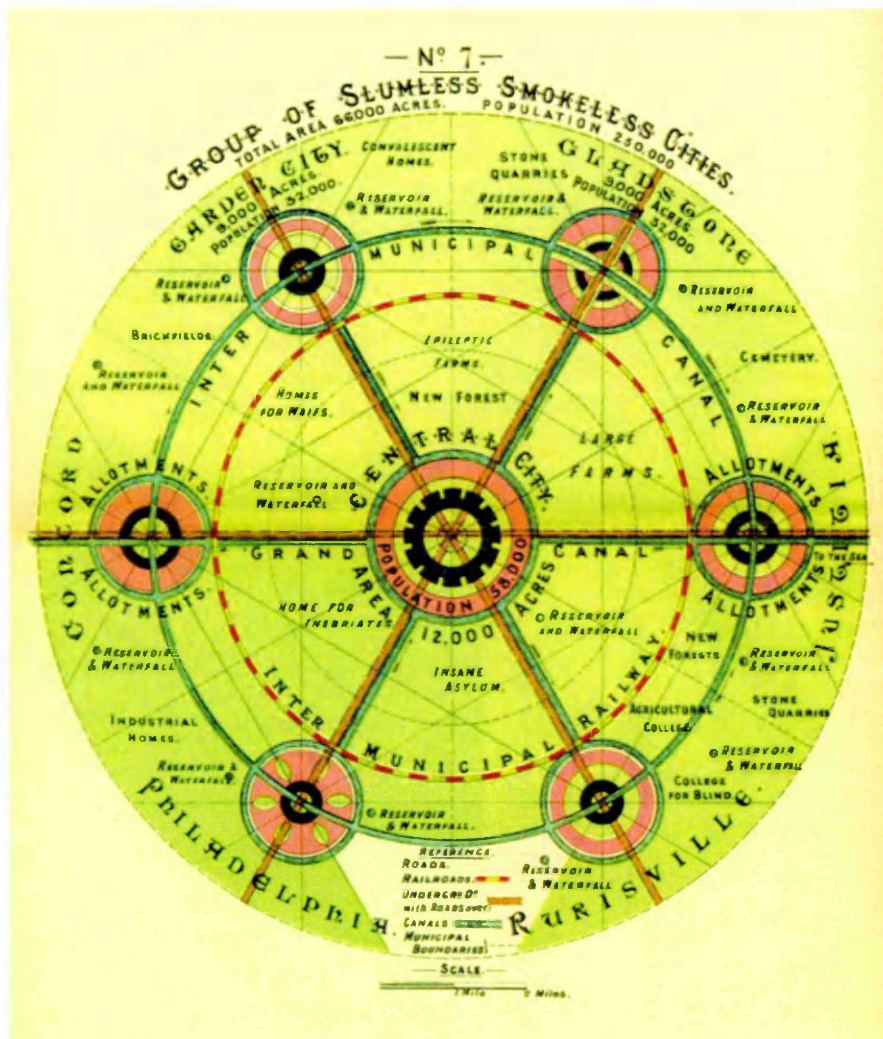


Figure 1. *Ebenezer Howard's original 'Garden City' concept (1902).*

The belief that buildings influence our behaviour is not a modern conception. This is reflected in the urbanism movement in architecture, which historically aimed to reform urban environments with the intention of changing behaviour. Projects in this field range from actualised schemes such as Ebenezer Howard's 'Garden City'(1902) to unrealised grandiose plans such as Corbusier's 'Plan Voisin' (1925) which proposed to demolish large swaths of Paris replacing it with uniform cruciform skyscrapers set within green space.

Despite the ambition of architects to influence our behaviour through architectural design, the explicit relationship between the built environment and social behaviour has been difficult to quantify. Space syntax theory, originally developed by Hillier and Hanson (1984), attempts to do this by providing quantitative and qualitative techniques for the representation and interpretation of the spatial configuration within buildings and urban environments. This is achieved by analysing architectural spaces such as streets, squares and public space as part of a continuous system in order to assess how well connected spaces are to their surroundings.

Space Syntax theory was developed as a result of Hillier and Hanson's early attempts to understand the link between architectural space and social behaviour in the built environment. The aim of these investigations was to answer key architectural and urban design questions such as whether the layout of cities has an impact on how people use streets.

Writing in 2003, Dursun and Saglamer argue that the distinctive characteristics of society are contained within spatial systems, 'In reality, characteristics of societies have a certain form with those spatial formations and the cultural differences between societies come to light by those refined structures.' (Dursun and Saglamer, 2003, pp 54.1). Architectural design is a sophisticated cognitive activity which transforms an initial abstract idea into concrete spatial formation (Dursun, 2007). Space syntax theory attempts to provide a tool with which to facilitate this process.

Peponis (2002) highlights the practical applications of space syntax as, *'an attempt to make explicit the spatial relationships that underlie our everyday experience of the*

designed environment and the way it functions culturally and socially' and states that the aim of the theory is to develop *'an understanding of the principles of spatial design and a critical evaluation of precedents and prospects'*.

Dursun (2007) examined the role of space syntax in architectural design and suggested four key features;

- Space syntax provides a language for thinking and talking about space, though Dursun argues that this language is possibly unfamiliar to architects as it is scientific and mathematical;
- The theory carries science-based knowledge into the architectural design process, providing a method for 'evidence-based design' (Hanson, 2001);
- It provides tools with which architects can explore their ideas and understand and show how their designs will work;
- Finally, and according to Dursun, most importantly, space syntax allows architects to explore their designs as 'living organisms' experienced by their inhabitants rather than through static evaluations, such as cost, level of light, energy consumption. (Hanson, 2001).

2.3.2 Visual Perception and Space Syntax

Space syntax was developed in the late 1970s at around the same time that Gibson was developing his ecological theory (Braund, 2011). In 1976, Gibson delivered a keynote address to the American Society for Esthetics, where he stated, 'architecture and design do not have a satisfactory theoretical basis' and mooted whether his

ecological approach to the psychology of perception and behaviour could provide this (Gibson, 1976, p. 413, cited in Braund, 2011).

Gibson's ecological theory (Gibson, 1979) has received considerable attention from researchers concerned with spatial analysis and space cognition and has influenced the development of spatial analysis theories. For example, Turner and Penn (2002) developed an agent-based simulation in order to explore human pedestrian behavior in architectural space. The theoretical justification of the simulation is derived from the requirement of individuals to behave with a vision-based mental model of the world, in which action is intrinsically connected to vision, as suggested by Gibson's ecological theory. Similarly, by developing an agent simulation where the only determinate of movement was the configuration of space, Turner and Penn showed that it is possible to emulate natural human movement patterns within a building by calculating the affordances in the context of natural movement (Hillier et al., 1993). However, the research was limited to very basic spatial configurations that included walls and openings and did not take into consideration complex components such as reflective or transparent materials or the possibility of integrated digital technologies. Current space syntax methods have not been tested to establish their ability to predict the relative magnitudes of pedestrian flows and concentrations in architectural spaces which have been modified by the introduction of virtual space. It could be theorized that should the virtual areas be included in the real space analysis then the space syntax measurements would work. However this is an untested hypothesis. In order to establish the relative impact of virtual space on people's

movement it is important to test the effect in real world situations. It may be that virtual space has a lesser impact upon movement than real space, as virtual space may be viewed and processed differently by observers than 'real space'. Additionally, superimposing virtual space onto real space is not a trivial task as it is likely to produce overlaps that cannot be analysed.

Indeed, similar criticisms can be made of all current techniques for spatial analysis that are cited in this review. None of these theories has considered the impact of complex configurations, pervasive technologies or digitally augmented space.

2.3.3 Space Syntax Methodology

To conduct Space Syntax analysis an 'axial map', which is a representation of the continuous structure of open space (Desyllas and Duxbury, 2001), is created. In simple terms, this is completed by accurately mapping the space and drawing a set of intersecting lines through all the spaces of the urban grid so that the grid is covered and all the potential circulation rings are completed. The subsequent analysis computes the relative depth of lines to each other. 'Depth' refers to the topological distance between spaces i.e. it measures the 'distance' of one space from another by counting the intervening number of spaces between them. The terminology to describe this depth shows how spatially integrated or segregated the line is. The data resulting from this analysis forms the base upon which maps which represent the distribution of spatial accessibility are drawn. These maps represent

the data in colour with red indicating accessibility (integration) through the spectrum to blue which indicates diminished accessibility (segregated).



Figure 2. Axial map of London – Red lines showing the most integrated pathways. Map image copyright: Space Syntax Limited.

Integration captures the depths of topological values by measuring the cognitive complexity of reaching a space. Therefore, it can be used to show how a space relates to its surroundings and the configuration to which it belongs. The production of an axial map makes statistical analysis of the relationship between relative segregation/integration and social data possible. For example, to examine whether

well-used commercial areas share spatial characteristics or whether there is a relationship between housing layout and burglary.

According to the theory highly integrated streets attract more people and in turn this attracts retail – which is dependent on footfall – resulting in a multiplier effect. This is the theory of 'natural movement' which is able to predict the potential effect of design on what Peponis (2002) describes as 'urban liveliness'. In the same paper Peponis provided a summary of the key factors in space syntax analysis:

- Topology – the possible paths that link any two locations.
- Directional structure – the number of direction changes along a path
- Metric properties – the distance between intersections, length of uninterrupted street lines and widths of streets.
- Integration – a measure of the closeness-centrality to identify streets which minimise directional or metric distances from potential destinations.
- Choice – a measure of betweenness-centrality to identify the most likely streets to function as through routes.

2.3.4 Critique of Space Syntax

In a recent paper, Ratti (2003) reviewed what he termed 'inconsistencies' within space syntax which make it 'difficult to accept that space syntax has the capacity to model pedestrian choice making' and that, 'the distortion of two ideal textures

produces a topological discontinuity, leading to the unacceptable situation where one single urban configuration produces two conflicting outcomes when analysed with space syntax tools' (ibid p.487).

In recent years space syntax has been used to model various factors to inform urban design, these have included pedestrian movement, traffic, criminal activity, potential for retail growth and pollution. Ratti notes that despite growing use of space syntax modelling within academia there is some controversy over its findings. This criticism focuses on the use of a simplified two dimensional representation of the environment which does not take into account the dimensions of the environment. Ratti questions, 'How is it possible to tell so many things about the urban environment with such a limited amount of information?' (p.488) and provides a critique of the method as summarised under the following subheadings:

Topology versus geometry

In space syntax all metric information is discarded, this is significant when considering pedestrian decision making. For an example of a problem associated with this: in space syntax two changes of direction are considered the same regardless of the distance inherent in these changes, one journey could be a mile long, and one could be a hundred metres but they would be considered as the same. Ratti suggests that space syntax only operates correctly in a regularly structured system, and that cities are more complex. However, Ratti also notes that Hillier suggests that axial maps do not ignore, but internalise the geometric properties of space, making them sufficient and allowing for the discounting of geometrical

information.

Axial map and building heights

All 3D information is lost in an axial map; therefore the height of buildings is not a factor in the analysis despite an assumption in space syntax that the grid is loaded with buildings more or less equally in its different parts. Ratti observes that the urban grid is very rarely loaded in a uniform way with building heights changing from one location to another along with a host of other influences which alter movement; 'bus stops, underground stations... the type of streets, such as their width, the ratio of sidewalks to vehicle lanes' (Ratti, 2003, p.492). According to Ratti, Hillier views these 'urban attractors' as a consequence of configuration, merely reinforcing natural movement. However, Ratti reports that, 'although this explanation can be seductive in the case of unregulated and organically growing urban systems, where attractors can influence urban growth undisturbed, it seems more arbitrary in the case of planned cities' (p.492).

Axial map and land use

Ratti reports that axial maps do not account for land use and that an adjustment to account for land use proposed by Hillier, namely that a spatial element can be added in the location of a retail unit to increase the integration of the location, is arbitrary and ambiguous.

Selecting axial lines

Ratti reports that several other authors have criticised the arbitrary process of selecting axial lines from real urban texture (Batty, 2001; Jiang and Claramunt, 2002).

In addition to these issues which have been recognised by other authors including Hillier, Ratti reports two further criticisms which he finds, 'exemplify some kind of short-circuit effect that appears when dealing with topological representations of the city, under certain geometrical conditions' (p.498).

The discontinuous nature of axial map transformations

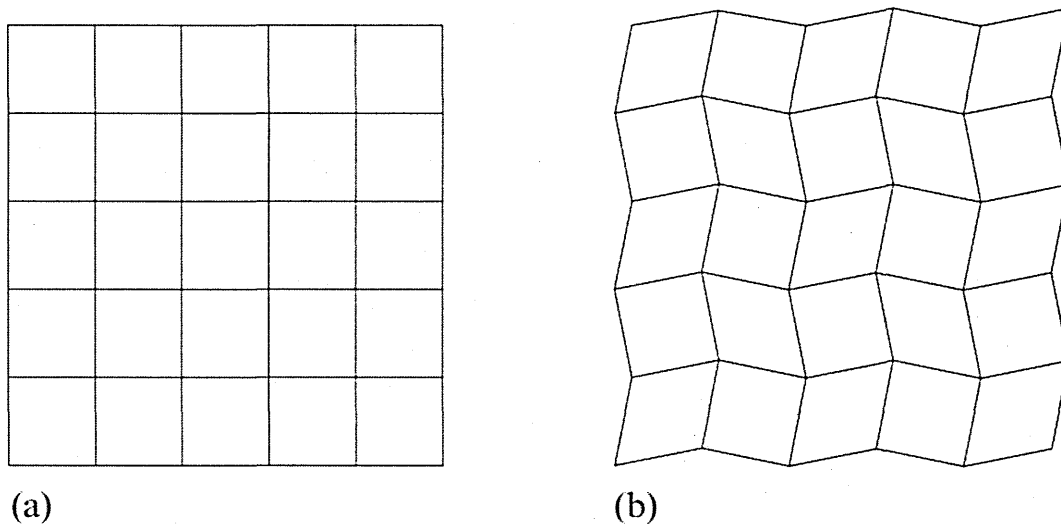


Figure 3. Illustrating Ratti's conception of an axial map with uniform integration (a) and adjusted with a skew (b) causing a centripetal integration pattern.

By skewing the axial map as shown in (b) in Figure 3 the integration values of the streets are altered from a uniform integration value across the map (a) to a

centripetal integration pattern. According to space syntax modelling very different patterns of movement would be predicted in these cases, people would be uniformly distributed in (a) and centrally biased in (b). Ratti notes that it is surprising that such similar configurations could produce such different results and furthers his argument by suggesting that if you reduced the skew of (b) so that it approached the form of (a) the axial map would remain unchanged until a critical angle was reached (see

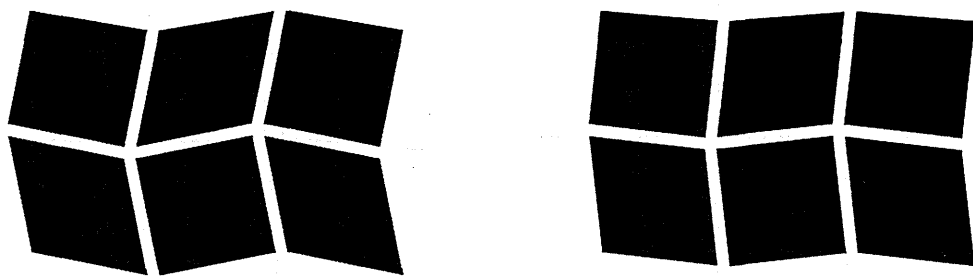


Figure 4) at which point sight lines would pass through from one street to the next resulting in sight lines represented in

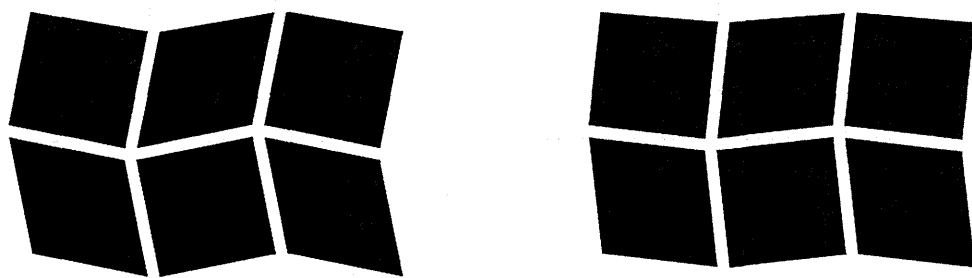


Figure 4 by the illustration on the right. At this critical angle if the same geometrical

arrangement is approached from one side or the other, two different axial maps with radically different integration patterns, are produced. Ratti acknowledges that this 'short-circuiting effect' does not undermine the theory in itself but that it presents logical problems, 'Can it be accepted that human behaviour as a function of urban configuration changes in quantum leaps or that pedestrians would respond in significantly different ways to virtually the same geometry'? (Ratti, 2004, p.496)

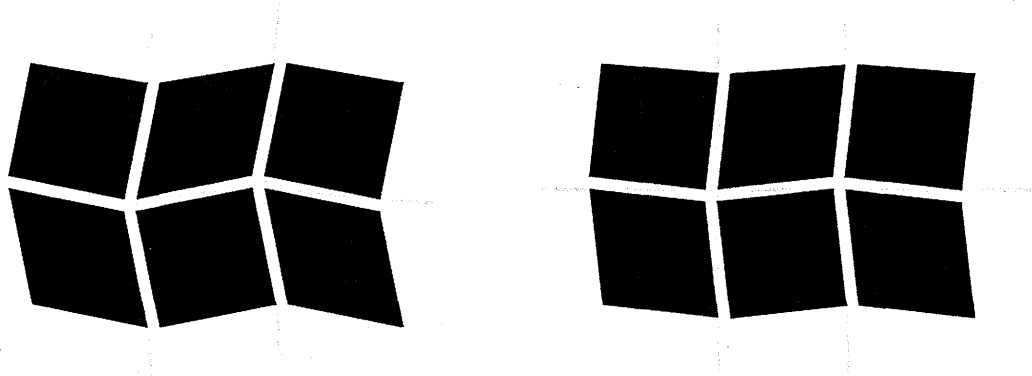


Figure 4. Showing Ratti's illustration of the effect of a small deformation of a grid which causes a 'short circuiting effect' (p. 495) where at a critical angle an abrupt change in the axial map is observed.

Axial map edge-effect

By putting two separate systems into communication with each, for example if a road was introduced, the integration patterns of the two axial maps are altered. The most integrated part would become the link between the two systems and the high integration which was a feature of the centre of the axial maps would be significantly reduced. Hillier identified this issue as the 'paradox of centrality' (1996, p. 340) which

states, 'Maximising internal integration also maximises external segregation'.

Ratti suggests that the paradox has not been fully explored and states that the results of space syntax analysis are influenced by the extent of the city being considered and that the edge effect has pervasive effects throughout the network, which affects results in remote locations. Ratti reports that though the problem has been addressed by other research which suggests using local integration to minimise the edge effects (Dalton, 1997), the work of Hillier et al., (1993), continues to be the primary reference relating to correlating axial map results with movement, and this continues to use global integration and leaves questions remaining about the area which should be included in axial analysis.

In conclusion Ratti notes that the problems associated with space syntax derive from the simplification of data, necessary in an era where computing resources were scarce, and that a deeper understanding of urban texture which is based on a full exploration of its metric and topological properties would contribute to the understanding of the influence of our environments.

This sentiment has been somewhat reflected by other researchers working in the field of spatial analysis, for example, Peponis (2002), states 'our intuitive understanding of space sometimes exceeds the power of available computational algorithms'.

Hillier and Penn (2003) responded to the issues raised by Ratti, identifying and examining a number of questions for space syntax, which are presented with a

summary of Hillier and Penn's responses below:

Can the same urban configuration give rise to different axial maps?

Ratti argues that axial maps are over sensitive to differences in built form, showing that hypothetically there can be sudden discontinuity in the axial map with only small continuous change in the metric situation. Hillier and Penn report that line discontinuity *can* come from a marginal shift in built form and question whether these marginally produced discontinuities are important in urban space, finding that they are, for two reasons:

- 'Just about' axiality – that is, where a line of sight is 'just about' permitted or broken through the positioning of buildings, is found regularly in cities across the world and is 'too common to have occurred in other than a rule-governed way'.
- Behavioural evidence – Hillier and Penn cite work by Dalton (2001) which asked people to navigate through two environments – with either an angular or orthogonal grid. They suggest that the findings show that given a minor geometric change in an environment people's behaviour in space is altered significantly.

Can space syntax deal with regular grids?

Hillier and Penn point out that in normal circumstances space syntax deals with regular grids without problems and that a theoretically pure orthogonal grid does not occur in urban environments for two reasons:

- Some lines will always connect to the outside, thus gaining significantly in their integration value.
- Urban grids that maintain an overall geometric discipline still differentiate lines configurationally by interrupting some lines and not others, as commonly shown in American grids which Hillier and Penn refer to as 'interrupted'. They cite the example of Grand Central Station, which whilst being part of a geometrically disciplined grid, interrupts the line of Park Avenue.

Does space syntax take into account such factors as building height and land use?

In contrast to Ratti's suggestion, Hillier and Penn report that space syntax is able to account for variables such as building height but this is dealt with separately, so as not to 'obscure the effects of spatial configuration by compounding it with other variables within the spatial model' (p.504). Instead, to incorporate the influence of other variables, such as building height, or road width, observational studies of the urban environment are carried out and their effects are assessed using statistical methods.

Does space syntax fail to deal with boundary conditions and edge effects?

Hillier and Penn report that the issues of boundary conditions and edge effects have been addressed within space syntax and that, 'by setting the radius of integration at the mean depth of the system from its most integrated line' (p. 505) a 'global'

analysis shows minimal edge effect or variation with the selection of boundary as shown by Hillier (1996).

Does space syntax, in general, discard 'precious metric information'?

Hillier and Penn reflect that earlier texts concerning space syntax were not explicit in their discussion of the relationship between topology and metrics in axial maps, and also that there is a fundamental problem when linking metric and topological information in configurational models of space. That is, when topological measures of an axial map are weighted, the integration pattern which results from configurational analysis will focus on the geometric centre of the system and decrease smoothly from centre to edge. This has two effects:

- A short backstreet close to the centre of a system can appear more integrated than a major line further away from the centre.
- The model becomes so sensitive to boundary choice that this defines where the centre of integration is.

Hillier and Penn argue that these factors would cause the relationships between spatial configuration and functional variables to be masked and state that it is for this reason that they deal with metric factors separately from the spatial model.

Does space syntax ignore land use?

Whilst they find Ratti *technically* correct in his suggestion that land use is ignored, Hillier and Penn suggest there are valid reasons for this. Whilst the notion of 'calibrating' lines with land use seems appealing, they argue, that to develop a

complex understanding of cities it is more productive to keep these factors separate in order to investigate the impact of both configuration and movement on land use, and the formation of centres and subcentres. Hillier and Penn acknowledge that there are real situations where understanding the effects of all variables on movement rate are required and reports that the 'Walkability Index', a collaboration between Space Syntax Limited and Transport for London (Stonor et al., 2002; 2003) builds a model which is able to do just that.

Are axial maps arbitrary?

Hillier and Penn report that a large body of empirical and theoretical evidence suggest that axial maps are anything other than arbitrary and report that a meta-analysis of axial line lengths across thirty six cities (Carvalho and Penn, 2004) confirmed this by identifying that the probability distribution of twenty eight of the cities collapse onto two master curves.

Hillier and Penn highlight that despite their simplicity, axial maps have, 'delivered striking results *on many different functional aspects of cities, and have also allowed the development of a theory of urban space, linking grid configuration, movement, land-use patterns, and centre formation, which has proved robust enough to use in design*' (p. 509) . They also agree with Ratti, that increased computational power will allow better analysis, but caution that the key feature of axial maps may be their ability to capture the properties of urban environments in a simple way.

Finally, Hillier and Penn robustly defend space syntax as a useful tool in innovative design, arguing that because it seeks to uncover the theoretical principles of how cities work spatially, it is not tied to copying existing urban phenotypes. They go further by suggesting that space syntax actively *promotes* change in urban planning, through being able to identify how functional patterns have changed, and therefore how urban environments should follow suit.

2.3.5 Visibility Graph Analysis

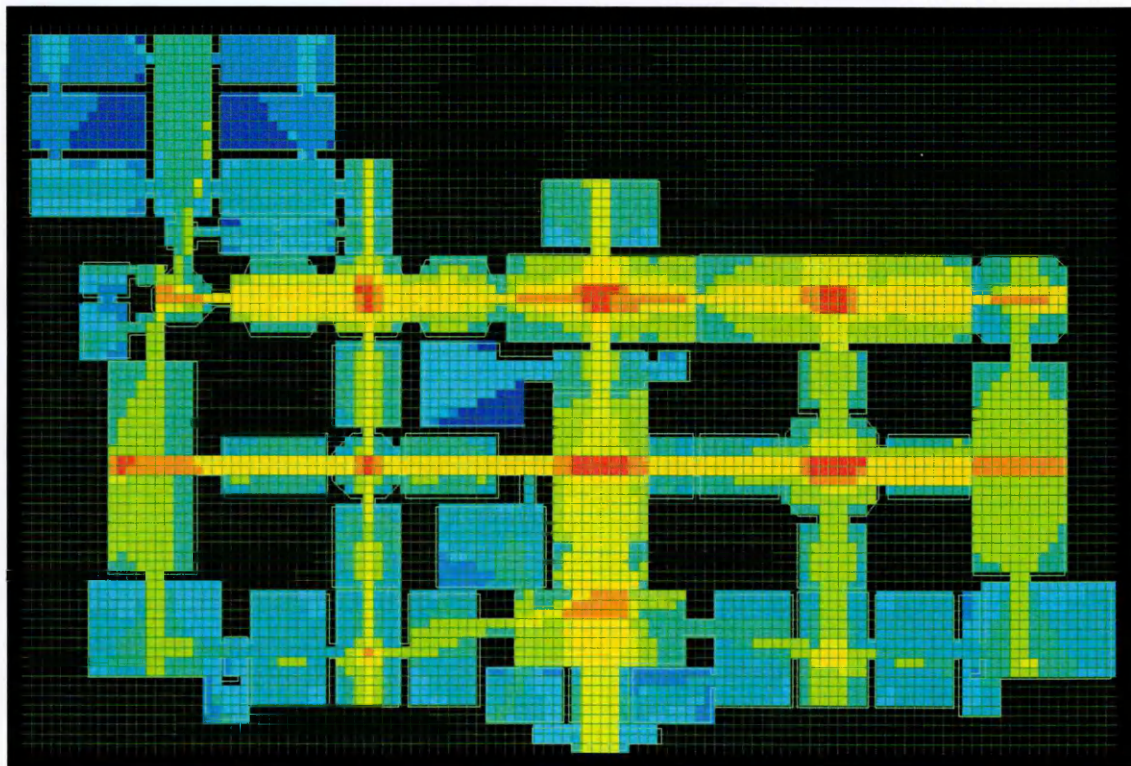


Figure 5. Showing a floor plan of the Tate Gallery, London, subjected to visibility graph analysis to show visual integration of the space.

Motivated by a desire to understand and improve people's experience of interior architectural environments, space syntax has been developed to analyse building

interiors through the development of Visibility Graph Analysis. This places the perspective of the user of architectural space at the centre of analysis by incorporating a further factor in the analysis, that of the visual field. These 'visibility polygons' (or isovists) are considered in conjunction with analysis of how users occupy and move through space to reveal what users are likely to experience in a setting.

Visibility graph analysis was developed by Turner et al. (2001) based on space syntax theory and early foundation work, such as that carried out by Thiel (1961), who attempted to record the details of the visual experience through buildings or urban environments by analysing the properties of spatial paths.

Whilst visibility graphs provide output which looks similar to that of axial maps it is important to recognise that they are measures of different factors; axial lines which predict movement and require some conscious thought on the part of the social actor, and isovists which measure and predict behaviour that is more dependent on the perception of the environment, and the environment's qualities.

The analysis of interior space is of particular relevance when considering the design of work environments – where it might be considered beneficial to facilitate the processes and improve productivity. Based on work with Steelcase, who design and manufacture architecture, furniture and technology products, Peponis (2002) suggested three factors of spatial design which can support knowledge-work and innovation in a workplace:

- Spatial design can support knowledge work by sustaining 'frequent work-related informal interactions'. At a local level these can be encouraged through controlled visual openness and the spatial grouping of workstations. At an organisational level, these interactions can be supported by making the environment more spatially intelligible – by having legible navigable plans, considering the distribution of key people who are central to interaction networks, and by ensuring movement paths connect with meeting spaces.
- Spatial design can allow 'visual traces of thought processes' to be made available in frequently used spaces with the use of equipment which can carry and redeploy visual display from one area to another.
- Spatial design can provide 'settings for different work styles' to support knowledge-work. These can be close or far from frequently used paths and activity hubs but placed within a well-integrated plan.

The concept of an 'isovist', which has had a long history in various fields of research including architecture, geography and mathematics, is central to visibility analysis. An isovist is 'the set of all points visible from a given vantage point in space and with respect to an environment (Benedikt, 1979, p. 47). Turner et al. (2001) argues that Isovists are an intuitively attractive way of thinking about a spatial environment because they provide a description of the space 'from inside', from the point of view of users as they perceive, interact with it, and move through it. As such, isovists have particular relevance to architectural analysis.

Tandy (1967) introduced the concept of isovists for the analysis of landscape but it was Benedikt (1979) who developed the method for the consideration of architectural space. Tandy conceived of isovists as a way to, '[take] away from the architectural space a permanent record of what would otherwise be dependent on either memory or upon an unwieldy number of annotated photographs' (Tandy, 1967, p. 9). A similar concept has a long history in the form of the 'viewshed' in the field of landscape architecture and planning (Amidon and Elsner, 1968; Lynch, 1976) and in terms of 'intervisibility' in computer topographic models (Gallagher, 1972).

According to Turner and Penn (1999), Benedikt's main contribution to the field was the development of a range of measures of the properties of isovists which include the, 'area, perimeter, occlusivity (the proportion of the perimeter lying on the solid boundary of the environment) and various measures of the distribution of the distance from the viewpoint to the perimeter' (p. 1). Benedikt created isovist fields by calculating the properties of isovists on a grid of locations and interpolating the data.

Benedikt starts by considering the volume visible from a location and then simplifies this representation by taking a horizontal slice through the 'isovist polyhedron'. The resulting 'isovist' is a single polygon without holes, as shown in Figure 6. The geometric properties are then considered, such as area and perimeter, and through this process the qualities of space, and its potential, are quantified.

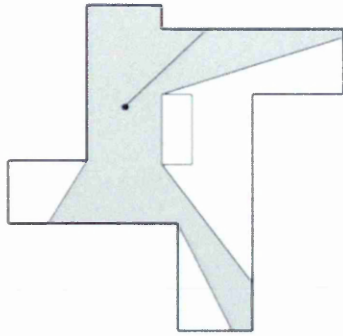


Figure 6. Example of an isovist, showing visible space from a single point.

Benedikt noted that analysis of multiple isovists is required in order to quantify a whole configuration and suggested that the way in which we experience a space, and how we use it, is related to the interplay of isovists. This led to the development of methods to calculate 'isovist fields' which record the individual isovist's properties for all locations in a configuration by using contours to plot the way those features vary through space. The closeness of the contours shows how quickly the isovist properties are changing and, according to Benedikt, this relates to Gibson's (1979) conception of ecological visual perception with 'textured gradients'.

Configuration is defined in general as, at least, the relation between two spaces taking into account a third, and, at most, as the relations among spaces in a complex taking into account all other spaces in the complex' (Hillier et al., 1987, p 363).

Turner et al. (2001) argue that despite the appeal of Benedikt's isovist methodology its use in architectural analysis has been limited due to two reasons. The first is that the geometric formulation of isovist measures means that they record only local

properties of space, and that the visual relationship between the current location and whole spatial environment is missed, including the isovist's internal visual relationships. The second is that Benedikt did not develop any guidelines on how to usefully interpret the results of the analysis, meaning that there is no framework to show how isovists relate to social or aesthetic factors.

Turner et al. (2001) developed the Visibility Graph Analysis methodology which they suggest can overcome the limitations they reported with Benedikt's theory. This incorporates how visual characteristics at locations are related and a potential way to draw social interpretation. The method draws from space syntax theory (Hillier and Hanson, 1984) and small worlds analysis (Watts and Strogatz, 1998) and produces a graph of mutually visible locations in a spatial layout which they termed a *visibility graph*.

Turner et al. (2001) suggest that through this graph numerous local and global measures of spatial properties that are likely to relate to perception of the built environment can be taken and compared with real life data of usage to 'shed light on the effects of spatial structure on social function in architectural spaces' (p. 104). Moreover, many studies have demonstrated a significant correlation between visibility analysis measures and the way people move (Desyllas and Duxbury, 2001; Turner and Penn, 1999). According to Turner (2002), there has been a reemergence of interest in the practical application of visibility analysis of architectural space.

2.4 Ambient technology

2.4.1 Ubiquitous Computing

'For thirty years most interface design, and most computer design, has been headed down the path of the 'dramatic' machine. Its highest ideal is to make a computer so exciting, so wonderful, so interesting, that we never want to be without it. A less-travelled path, I call the 'Invisible'; its highest ideal is to make a computer so imbedded, so fitting, so natural, that we use it without even thinking about it.' Weiser (1996)

Ubiquitous computing is a concept developed by Weiser (1991) and refers to the permeation of computers into the life of the user so that they are fully integrated and, 'become a helpful but invisible force, assisting the user in meeting his or her needs without getting in the way' (Weiss & Craiger, 2002, p. 44).

The term emerged in the late eighties and early nineties when Weiser (1991) postulated a model of human-computer interaction in which information processing would be completely integrated into everyday objects and activities, stating, 'The most profound technologies are those that disappear' (Ibid: p. 3). The core of the concept is not that computers would become ubiquitous but that, 'The transparency of the interface that determines the user's perception of digital technologies' (Ishii, 2004, p. 1299).

Buxton (1995) described the characteristics of ubiquitous computing:

- Ubiquity: Interactions are not channelled through a single pathway – access to a digital entity is 'everywhere'.
- Transparency: Technology is unobtrusive and as integrated into the ecology of architectural space as, for example, chairs or desks.

The concept of ubiquitous computing has frequently been interpreted as the introduction of digital technologies in all aspects of daily life, 'anytime, anyplace'. These interpretations tend to focus on 'foreground' tasks in human activity but do not consider 'background' processing of information. According to Buxton (1995) 'foreground' tasks are those which humans actively attend to and are therefore conscious of, for example, speaking on the telephone. Background tasks are those which humans are not required to attend to, and can take place on the periphery, for example, a light automatically switching on when a person enters a room.

At present the requirements of ubiquitous computing seem unmet. Whilst more functions of computing are developed and the number of devices is rapidly increasing there seems to be less focus on embedding these in the physical environment to provide the seamless integration of ubiquitous computing which Weiser envisioned.

Like Weiser, Negroponte (1995) acknowledged that in the future, computing would be integrated into the physical world. Negroponte discussed the co-existence of 'atoms' and 'bits' noting that atoms make up physical objects and bits are digital information. He postulated that in the future, information which is currently made of atoms will be made of bits. Negroponte asserted this view speaking at a conference

in 1996 where his response to a newspaper owner who asked about the future of his industry was, 'The unfortunate thing about newspapers is the word *paper*' (Matthews, 1996) and the industry wide shift towards digital presence in the intervening years have shown that, at least in this respect, his beliefs were justified.

Recent work by Chalmers and MacColl (2003) challenges what they see as the dominant paradigm in current design, that of seamlessness, one of Weiser's key requirements in ubiquitous computing. In their paper, 'Seamful and Seamless Design In Ubiquitous Computing' they suggest that, 'letting a ubicomp system be itself means accepting all its physical and computational characteristics – that may either be weaknesses or strengths...the idea is to shift from designing seamless technology and instead design for seamful interaction'.

2.4.2 Ambient displays

'Instead of various information sources competing against each other for a relatively small amount of real estate on the screen, information is moved off the screen into the physical environment, manifesting itself as subtle changes in form, movement, sound, colour, smell, temperature, or light. Ambient displays are well suited as a means to keep users aware of people or general states of large systems, like network traffic and weather'. Wineski et al., (1998, p. 2).

In contrast to the traditional graphical user interface which focus on isolated users and foreground activity, ambient displays can make use of the entire physical

environment as an interface for digital information which can be conveyed in a variety of ways; through light, sound, movement, colour or temperature.

Wineski et al. (1998) compared the natural world's capacity to engage our senses with peripheral ambient displays with their vision for the future of interfaces between humans and digital information. They explored the capacity of architectural spaces to be integrated with digital information, where ambient displays could be the medium for transferring information between the physical and virtual world, for example, the projection of another physical world, or information carried from the environment, such as the time of day or weather conditions.

Traditional Human-Computer Interaction platforms focus digital information on small screens and neglect human's ability to process background information without needing to focus foreground activity on a task. Ishii and Ullmer (1997) moved beyond this paradigm, illustrating the concept of ubiquitous or invisible computing, by suggesting 'Tangible User Interfaces' (TUIs) to describe the integration of virtual and physical worlds, where digital information is merged with everyday objects.

"We see the locus of computation is now shifting from the desktop in two major directions: i) onto our skins/bodies, and ii) into the physical environments we inhabit."

(Ishii & Ullmer, 1997).

Ishii and Ullmer's vision of 'Tangible Bits' centred on the integration of cyberspace into the physical environment through the development of an interface between humans and digital information. The work is based both on Weisser's ubiquitous

computing, which demands an invisible delivery of information, and 'Augmented Reality', which explores the integration of the real world and computational media through display devices or video projections (Wellner, 1993). 'Tangible Bits' examines the transition of people's attention between background and foreground with the use of interactive surfaces, graspable objects with embedded digital information, and ambient media. In order to blur the boundary between the physical and digital world, Ishii and Ullmer envisioned, 'the coupling of bits with graspable physical objects; the transformation of architectural surfaces into active interfaces between physical and virtual world; and the use of ambient media at the periphery of human perception'. (Ishii and Ullmer, 1997, p. 1)

A similar approach to systems that rely on embodied interaction, tangible manipulation, physical representation of data, and embeddedness in real space, is the framework for tangible interaction developed by Hornecker and Buur (2006). The aim of this research was to understand the user experience of tangible interaction and analyse its social aspects. Tangible interaction was classified into three basic forms: the *data-centred view*, which offers interactive coupling of physical artefacts with digital information and is close to Ullmer's and Ishii's vision (1997) of human-computer interaction; the *expressive-movement-centred view*, which emphasises bodily interaction with objects; and the *space-centred view*, which supports whole body interaction in physical spaces with embedded digital displays and ambient media. In line with this classification, they designed a framework based on the characteristics of an interface associated with the notion of tangible interaction. The

main properties of such an interface are: tangible manipulation that is directly connected with the materials used for the construction and representation of the interface; spatial interaction, which refers to the embeddedness of the interface in space; embodied facilitation that illustrates the emergence of social interaction as a result of spatial and objects' configurations; and expressive representation, which is the outcome of using decipherable material and digital representations.

2.5 Ambient displays in architecture

'When physical space is extended to a virtual world through a display placed on a wall, opacity gives its place to transparency, static becomes fluid and boundaries are dissolved'. Ataman et al., 2006 Page number.

2.5.1 Historical context

The development of technology which allows digital information to be integrated in architectural space is a very recent phenomenon. Digital technologies can be used to manipulate space by altering the perceived boundaries of architecture, influencing how we relate and behave in our environment. The manipulation of space in this manner is certainly not a new phenomenon, reaching a peak of popularity in the 17th Century when Baroque artists championed a form of trompe-l'oeil painting referred to as Quadratura which was based on emerging scientific theories of perspective (see Figure 7). The style was used to create architectural illusions; expanding actual space into an imagined space, confusing boundaries, and blurring the difference between physical architectural details and manipulated space.



Figure 7. *'Triumph of Sant' Ignazio of Loyola'*, Andrea Pozzo, 1691-94. Ceiling fresco, Chiesa di Sant' Ignazio, Rome.

In a form of modern day trompe-l'oeil, Müller transforms the flat surface of a pier into a dramatic ice age scene where members of the public are invited to interact, perching on the edge or seemingly defying gravity by walking through the painting and over the crevasse (see Figure 8).



Figure 8. '*Standing on the edge of the crevasse*', Edgar Müller. 3D pavement art, Dunleary, Ireland. 21st-24th August 2008

2.5.2 Ubiquitous Computing in Architecture

Drawing from ubiquitous computing theory (Weiser, 1991), Ishii and Ulmer (1997) envisioned the transformation of architectural surfaces into active interfaces between physical and virtual worlds where smart materials which can adapt to external stimuli and technological advances are used to improve architectural space, creating environments that are adaptable to human needs.

Research suggests that the use of digital technology in architecture, beyond simply modifying the aesthetics of space, can influence people's behaviour (Rogers, 2010;

Dalton, 2009). A digitally augmented architectural space can affect people's perception of their surroundings therefore their behaviour within it.

The introduction of virtual space into the physical environment redefines the spatial properties of the environment. For instance, an ambient display can be used to transform a static wall into a transparent or changeable space which dissolves the boundaries between virtual and physical space. O'Shea's 2007 interactive installation, 'Out of Bounds' set at the Design Museum, London, effectively challenged the relationships between physical and virtual space by projecting previously recorded spaces onto the walls of a room. O'Shea enabled people to 'see' through the physical boundaries of space by providing them with an 'x-ray torch' which, when aimed at the wall, revealed secrets hidden behind them, 'This interaction allowed people to enter the 'prohibited' areas of the museum while encouraging their childlike curiosity'.



Figure 9. 'Out of bounds' installation – O'Shea (2007). A participant aims their 'x-ray' torch at a wall to reveal hidden images.

2.5.3 Mediatecture

The introduction of ambient technology in architectural space provides a new way for people to interact with digital information. Through the use of ambient displays digital information can be embedded into environments, and displays can be altered in order that the environment is fully adaptive. The incorporation of multimedia technologies into architectural space has led to the notion of 'mediatecture' (Tomitsh, 2008). These are systems that 'extend architectural environments, typically in public or semi-public contexts.' 'Mediatecture applications affect their immediate architectural environment and change the way people perceive and interact with their environment' (Tomitsh, 2008).

Recent architectural projects have shown that increasing attention is being paid to the potential uses of embedded digital technologies. The Munich based BMW Museum designed by Atelier Brückner in 2007 uses an installation of large ambient displays in the wall space of about 706 square meters (See Figure 10) According to BMW this shows, 'New approaches to intertwining architecture, exhibition design and communicative media'. ART+COM completed the interactive system which is capable of displaying 30 possible light displays and De Zeen magazine (July 2008) describes the effect; 'The parked vehicles on display almost seem to move as the multimedia light reflections progress across the cars, and architecture and scenery is

briefly reflected in the polished varnish of the roadsters... The architecture is dematerialised and given a new dynamic attitude'.

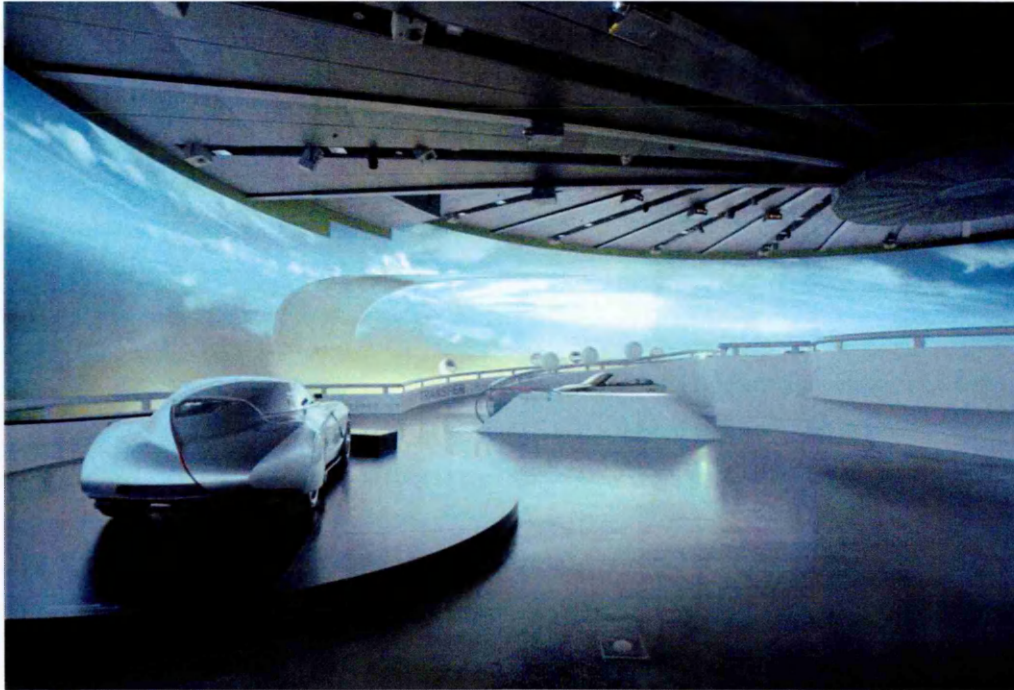


Figure 10. BMW Museum, Munich, Germany

Similarly, the 'Digital Pavilion' in Seoul designed by Oosterhuis_Lénárd and completed in 2006 transforms architectural space with digital displays. The walls of the pavilion are formed by a complex adaptive robotic system of interacting installations which respond to each other and the public. This creates a unique user experience where people can interact with the installation using a handheld device, 'Navigating the interior feels like walking in the interior of a living installation. You are inside technology: ubiquitous computing at its full potential. Installations interact with the public but also with other installations'. (Calabrese 2009)

2.5.4 Understanding spatial relationships in digitally adapted space

Ambient displays in architectural space have the potential for numerous uses, for example changing the aesthetics of an environment, providing information, and engaging people, whilst at the same time remaining unobtrusive. In most circumstances the displays replace walls, therefore the morphology of the space is not altered but a static space can be transformed into a dynamic interface. The interface created by the digital display can be considered as a virtual opening or a 'digital window' which extends architectural space as perceived by users. Indeed, they can be used to simulate the existence of a window by delivering information about the space behind itself.

Ambient displays can be used to manipulate the perceived physical relations of a space. The added complexity of the architectural space when a digital system is introduced means that human interactions within the space are more complex than in a traditional space. The interaction system must account for the user, the digital display and the environment which contains both (Dalton, 2009)

Interactions occur between:

- Human and digital system
- Human and environment
- Digital system and environment
- Human and human
- Digital system and digital system

When all of these relationships are simultaneously active, the result is a responsive environment (Bullivant, 2006); a digitally enhanced social space that engages people in interaction with each other, as well as with their environment. This research highlights how architectural design needs to consider the impact of digital augmentation of space. To be able to do this, a better understanding of the effect of digital technology upon people's behaviour in space is required.

2.5.5 Pervasive Expressive Architecture

The introduction of digital information into architectural space led to the development of the term, 'pervasive expressive architecture' (Tomitsch et al., 2008) to describe the relation between physical space and the virtual world. '*Pervasive expressive architecture* is defined as spatial representation of specific information relevant to the immediate environment or people who use that space'. Tomitsch et al. (2008) developed a framework with which to classify and design digital information applications which augment architectural environments. The first dimension of the framework was formed by the potential layers of architectural space in pervasive expressive architecture:

1. Façade – the exterior surface.
2. Interior – fixed surfaces, like walls and ceilings but not their structural arrangement. For example, a wall in a building that has been augmented with digital information.

3. Structure – the foundation and load-bearing elements, the interior layout.

‘Examples within this layer introduce new structural elements into the architectural space, such as a wall that acts as a display’.

The second dimension of the framework is formed by three categories which Tomitsch et al. (2008) term ‘embodiments’ which refer to the level of interactivity which they support.

1. Expressive medium – the architecture is used as a medium of expression, affecting how users perceive their surroundings and potentially engaging them in dialogue with other users. However, they do not engage users in direct or indirect interaction with the architectural space. A typical example in this category would be the use of ambient displays.

According to Tomitsch et al. (2008) applications in this category, ‘should be calm, non-obtrusive and opportunistic, revealing information only for interested inhabitants or passers-by, in order to avoid distraction for other people in their vicinity’. In addition to these characteristics, Pousman and Stasko (2006) proposed the term ‘ambient information systems’ (AIS) to describe technologies that inform people without being unnecessarily distracting, and suggested that peripheral displays should be aesthetically pleasant; display information that is important, but not critical; be able to move from the periphery to the focus of attention; focus on tangible representations in the environment; and provide subtle changes to reflect updates in information.

2. Responsive space – an environment that interacts with people who pass through it. This could be embedded with sensors, displays and networking technologies which allow tracking of people, movement and environmental conditions.

The aim of applications in this category is to create a digitally enhanced space, inviting people to interact with the environment as well as with each other. In addition, they should also be interactive and enjoyable.

3. Social actor – the space is viewed as an embodying social actor so that it is perceived by users as a social character and can evoke emotions from humans, such as need to take care of it. In addition to the factors contained within the first two categories of embodiments these spaces are also social and adaptive.

The research and design of innovative applications demonstrate that information interfaces are no longer being limited by traditional personal computing designs, and that there is real capacity and potential for ambient displays to be usefully integrated into architectural space.

Information can be presented to the senses in a manner in which it can be processed in the background of awareness but can also be moved into the foreground by the user, who can control it through their personal state of awareness or even through physical controls (Wisneski et al., 1998). By using the tactic of embedding information into the

periphery of human attention (Cadiz et al., 2002), ambient displays introduce a new approach to interfacing people with digital information.

As Altosaar et al. (2006) state, the main principles of designing an ambient display are to avoid the foreground display, to sense the user's interest across devices and to negotiate user's attention with the use of sensors. These assumptions can lead to the notion of calm computing (Weiser, 1998) which fluently moves from centre to periphery and back. By bringing more details into the periphery, calm computing can improve people's peripheral reach (Weiser and Brown, 1995). In this way, disruptions are avoided and interfaces can switch from the background to foreground styles of display fluently to achieve an optimal distribution of user attention across multiple tasks.

Ishii et al. (1998) experimented with ambient displays as an approach for interaction between people and digital information. They designed the 'Ambient Room', which connected people within the room with the exterior physical environment. This was achieved through the use of aural soundtracks of birds and rainfall and displays of information about time. This project was one of the first to address the design of Calm Computing (Weiser, 1998), in which technology must engage the periphery of users' attention not the centre of their attention. In Ambient Room users were allowed to assimilate ambient information in parallel to a focus task. However, as Wisneski et al. (1998) argue, the simultaneous use of media elements in 'Ambient Room' caused displays to exhibit a lower threshold for the background to foreground transition and as a result an 'information overload' was created. By extending this

project to 'Ambient Fixtures', Dahley et al. (1998) took components of the Ambient Room and distributed the displays in architectural space. Ambient Fixtures presented the vision of standalone ambient media displays able to shift the use of ambient media from a private context to more communal environment.

As Gaver et al. (2003) state, 'In order to design systems that are integrated, engaging and evoking, it is necessary to use ambiguity as a resource for design'. According to Gaver et al. (2003) ambiguity allows for multiple readings of the same data, within the informatics model. By introducing the notion of ambiguity in their description of a spatial system, Mathew and Taylor (2008) explore how better interpretations of information can emerge. Based on the beliefs of Maeda (2006) that simple interfaces appear simple to humans because they blur interpretation into one image of simplicity, they introduce the term 'ludic ambiguity' to describe the interaction that results from abstraction. Their project, 'AuralScapes' attempted to blur information which is derived from people's subjective interaction with an interface in a situated context into the physical space. Simultaneously, they address a tangible interaction problem. With the use of sound and sky projection, AuralScapes created a visual connection from the outside to the inside, where information is abstracted and delivered at the periphery of human attention. Like the Ambient Room, AuralScapes is designed to bring people inside the computer i.e. it refers to static relation between human and space, and thus it ensures a pleasant environment to live in but does not support further social interaction.

Similarly to the AuralScapes installation, Erickson and Kellogg (2002) argue that in order to support communication, digital systems should provide virtual 'windows' that let people see each other. Like a window that carries information about the environment, an ambient display can act as a virtual 'window' that links physical and virtual world (where virtual world may refer to a projection of another physical space). The embedded information in the network can be visual, tangible, or audible transforming static architecture into dynamic informatics systems that affect perception of space and the movement within them.

2.5.6 Behavioural impacts of digitally adapting space

In addition to transforming the aesthetics of architectural environments, the use of digital displays can influence people's behaviour within the setting. Röcker et al. (2004) state that ambient display installations that promote awareness produce positive effects and behavioural change in office teams.

Rogers et al. (2010) demonstrated that people were influenced by ambient displays which 'nudged' people when confronted with a decision between taking the stairs and using an elevator. Interestingly, whilst people reported that they were not aware that they changed their behaviour, data showed that there had been a significant change in stair/elevator use.

Research has shown that changes in the environment through digital augmentation have led to behavioural changes in people using the space. Fatah gen. Schieck et al. (2007) installed an interactive floor in public space and recorded the reactions of

people using the area in an attempt to understand people's responses to the space. The researchers reported unexpected and diverse changes in movement patterns and recorded that people interacted with the installation in varying degrees from a peripheral awareness, to focal awareness, to direct interaction. In addition to this, most of the people using the space shared the experience with friends and a few shared the experience with strangers creating unexpected social interaction.

Some researchers have focused specifically on the use of ambient displays to create social engagement arguing that the integration of digital information into the physical environment can facilitate new forms of interaction (Kjeldskov and Paay, 2006) and encourage social interaction (Bullivant, 2007).

In order to understand people's behavior and movement in a space a close examination of the meanings and social factors that are embedded within the environment is required. Fischer (cited in Shklovski and Chang (2006), p. 36)) stated that People navigate both through physical movement and interpretations of social context In addition, the development and integration of computer systems in public space demands an understanding of physical space and how it impacts the social interactions that it supports (Kjeldskov and Paay, 2006).

Harrison and Dourish (1996) argue that physical space is structured according to uses and needs for interaction. They suggest that as a result of this, observation of these actions and interactions, the 'affordances' of space (Gaver, 1992), is required in order to be able to understand it.

As noted, ambient displays can be used to present information on the periphery of awareness, so that people need not attend or focus directly on the display in order to understand the information being conveyed. Therefore, the concept of awareness in human computer interaction needs to be examined. Based on Dourish and Bellotti's (1992) definition, awareness is, '[an] understanding of the activities of others which provides a context for your own activity' (p. 107).

It is important to analyse all the qualities of a designed space in order to be able to design an efficient interface which has the capacity to influence human behavior. As stated by Shklovski and Chang (2006), the aim is not to turn designers into social scientists or urban planners but that in the process of design, the wealth of research in these areas should be taken into account. 'Collaborations are crucial to understanding social life and creating technologies that can augment it in positive ways' (Shklovski and Chang 2006, p. 28).

Harrison and Dourish (1996) argue that whilst many designers use spatial models to support interaction it is a notion of 'place' which frames interactive behaviour. Defining their principle as, 'Space is the opportunity; place is the understood reality' (ibid: p. 67) they draw distinction between place and space, and focus on the social meanings and cultural understandings about behavior and actions within physical space.

Architectural design researchers and theoreticians have long considered the relationship between human activity and space (Lynch, 1960; Alexander et al.,

1977). However, there is a dearth of information in the body of research when considering the role of integrated technologies.

Telhan (2007) developed a public interface with the intention that it functioned like a social catalyst in public space, reflecting the social identity of the environment and increasing user's sensibility towards the place and other people in the environment. Telhan examined the boundaries between places, people and media and identified four integral boundaries which exhibit great influence over people's activities in architectural space.

Firstly, Telhan states that spatial boundaries segregate people. Different forms and levels of access affect the formation of diverse social groups. The affordances of an architectural space shape people's action, behavior and identity. Secondly, drawing from the work of Lippard (1997), Telhan identified social boundaries, suggesting that the social identity of a place is determined by the diversity of people who inhabit it.

The third boundary was that between people and public media - people do not physically or functionally shape public media and therefore, in general, public displays are not interactive, but are to be viewed passively.

Finally, the fourth boundary suggested was between architecture and media. Telhan argues that despite new buildings often being augmented with digital screens these surfaces frequently ignore the social aspects of the environment and merely broadcast propaganda, neglecting the integration of digital information to create engaging interfaces.

Regarding the boundary between people and media, as a result of the materiality of interfaces, evidently lies in the inherent nature of the physical and digital worlds. In contrast to digital information which is transient and able to support new meanings and functionalities, physical objects are stable and support specific forms and functionalities (Coelho and Maes, 2008). Currently, the stability of physical objects limits the potential for moving from simple points of interaction to the development of fully adaptive environments.

In contrast, the introduction of new responsive and adaptable materials will provide new ways in which architectural space can reconfigure itself by reshaping the boundaries among humans, space and digital information and also by setting the user as the definite role for creativity.

Acknowledging and understanding the boundaries that are formed by architectural space provides the potential for the placement of ambient technology to influence the way people perceive their surroundings and engage them in social activities. This would generate new possibilities for using digital technologies not only as information systems but also as active components of space affecting communication and functionality.

When researching and considering architectural spaces, it is common to differentiate between public and private spaces. However, according to Greenberg et al. (1999) the terms 'public' and 'private' merely suggest extremes in a spectrum and the boundary that distinguishes privacy and publicity is refined according to current conditions (Palen and Dourish, 2003). As Fatah gen. Schieck et al. (2006) suggest,

people interpret spaces as: 'public', which are open to everyone; 'private' that promote a sense of security and seclusion; and 'social' that cover the range between public and private. However, architectural spaces cannot be strictly categorised, as the boundaries are blurred and mobile. In addition to the classification of architectural spaces, while examining the emerging relationships in a pervasive system, Kostakos and O'Neill (2005) and Kostakos *et al.*, (2006) propose that this can be considered as the combination of three spaces: 'architectural space', which has embedded values and understandings that tend to frame human behavior; 'interaction space' which is created by designed artifacts; and 'information spheres', which refers to dynamic digital information. In order to achieve a real integration space, these three spaces must be taken into consideration as a whole and information should be featured in respect of social content (Fatah gen. Schieck, 2005).

2.6 Conclusion

'When space syntax engages problems that are specific to a field of practice or inquiry, it unavoidably interacts with new questions. These new questions require both extending space syntax techniques and interacting with other forms of data and other disciplines of analysis that relate to the question at hand' (Peponis, 2002, p4.)

The literature review demonstrates that whilst research has developed methodologies for the analysis of people's movement in architectural space none of these methods can account for the influence of ambient projection and the digital extension of space.

While there is a large body of data concerning human-computer interaction there is a dearth of information considering the environment and its role in this relationship. However, when considering the integration of digital information in architectural space it must be recognised where the interaction that occurs is between humans, digital systems, and the environment that contains both (Dalton, 2009).

Therefore, by exploring the relationship between architectural spaces, digital augmentation and human behaviour this research can provide an improved understanding of how to design spaces with embedded ambient technologies

"The intersecting issues of spatial context, pervasive digital technologies and sociality need to be understood when designing for inhabitant's interactions within these hybrid spaces". (Agre, cited in Paay, et al., 2009, p 7.2)

The recent advancements in digital technology have radically altered how individuals relate to one another and to their environments (Mitchell, 2003). In a world where ambient technologies are increasingly being used to transform static architecture into dynamic space (Ataman et al., 2006) it is essential for architects to understand the impact of these technologies on people's movement, in order that they can design efficient spaces.

Historically, architects could rely on traditional spatial analysis techniques, such as Space Syntax, to analyse users movement in designed space, however, these techniques do not account for the presence and potential influence of ambient media, and examine only basic architectural elements. Additionally, researchers in the field of ambient technology have focused their attention on the interaction between people and ambient technology, to the neglect of the interaction between people and the space, that the technology is situated.

This work presented in this thesis is founded upon an extensive body of research, which has its origins in Gibson's ecological theory (Gibson, 1979), Benedikt's development of isovists (1979), Hillier and Hanson's space syntax theory (1984), and Visibility Graph Analysis (Turner et al., 2001). Whilst this rich body of work provides a firm foundation upon which to understand spatial relationships in architectural space, recent developments in technology have prompted the design of innovative digitally augmented spaces, and this presents a problem for the current theories as they exist. As shown by the literature review, current theories do not have the capacity to account for visual depth in architectural space introduced through digital

augmentation. The potential effect of this type of manipulation upon behaviour has also remained unexamined. The theories which have been discussed are only able to account for openings and solid walls in their methodologies whereas, placements of digital elements in physical space introduce a transparent layer of a dislocated virtual depth. While other studies (Mathew and Taylor, 2008) have considered this interface as a digital link between the outside and inside; the argument put forward by this thesis, and which forms the basis of the hypotheses presented, is that the digital opening is a virtual window that extends both architectural space and the vision of users in a given space. Like a window that connects two physical spaces transferring information between them, an ambient display can be seen as a link between physical and virtual worlds.

CHAPTER 3 - METHODOLOGY

3.1 Introduction

3.2 Experimental design

3.3 Data collection

3.4 Method for data analysis

Chapter 3 - Methodology

3.1 Introduction

Methodology can be described as the philosophy of the research process which, 'includes the assumptions and values that serve as a rationale for research and the standards or criteria the researcher uses for interpreting data and reaching a conclusion' (Bailey, 1982, p. 26)

A methodology involves the identification of a problem to be solved, generation of questions relating to the problem, formulation of a design which can solve that problem, data collection, analysis, and finally, interpretation of the results to answer the questions.

Human computer interaction (HCI) is a young discipline which has developed over the last thirty years. The origins of the discipline are within computer science and cognitive psychology, with influences from sociology, anthropology, ergonomics and design. The multidisciplinary nature of HCI means there are numerous methodological approaches employed to conduct research in the area.

Underlying any research is a set of assumptions about the nature of social reality and how we can investigate and learn about it. As such, when conducting academic research it is important to consider the choice of methodology to ensure that the

research question can be answered correctly.

Positivism is a philosophy of science which recognises only that which is able to be scientifically verified, in the form of empirical evidence. The paradigm rejects introspective and intuitive knowledge, ignoring culturally defined phenomena and is associated with the experimental method. Positivist methods typically look for explanations through cause and effect and are concerned with researcher objectivity.

In contrast, antipositivism, or interpretivism describes an approach which views social science as less deterministic and within which researchers aim to understand and interpret phenomena. Antipositivism is associated with qualitative research methods which are exploratory and often conducted in the natural environment, for example, conducting observations of people. Antipositivist methods view the researcher as an integral part of the research with an interpretive role.

A further distinction between the two approaches is that antipositive research is typically concerned with drawing comprehensive information from a small, often unrepresentative pool of participants whilst positivist research provides numerical evidence which captures a large amount of data and can be used to test hypotheses. (Burns, 2000).

The research presented in this thesis is aligned with the positivist paradigm. The presence of an established theory which accounts for people's movement in space provides a foundation for the work. A series of quantitative experiments provide a method through which the limitations of this theory can be examined. This is

achieved by systematically manipulating a series of variables in an experimental setting which, whilst controlled, is designed to replicate a typical architectural environment to ensure the validity of the results.

The experimental approach employed in this research provides a method to test hypotheses in a systematic way and ensure the replicability of the research to enable other researchers to further explore the findings and potential limitations.

3.2 Experimental design

The literature review presented in Chapter 2 identified the need to explore the effect of digital augmentation of physical space upon people's perception and movement within it and the implications this has for current theory. To do so, the experiments described by the thesis were designed to examine an overarching hypothesis, which is as follows:

Ambient displays can be introduced into physical architectural settings to augment the perceived visual depth of a space by virtually linking and extending physical space towards another real or virtual space. This augments the topological and visual relations of a space which influences how people use and move within such settings.

The experimental scheme was based upon testing variations of hybrid space in which the physical space remained constant whilst the variable, digital augmentation, was manipulated to measure the effect on people's movement.

Whilst space syntax researchers typically observe people's natural movement in 'real' spaces, here the approach was to observe people's movement within an artificial, and therefore experimentally controllable, environment. This type of research is typical in psychology and human-computer interaction studies.

The decision was taken to conduct the experiments in artificially created public architectural spaces. Since these spaces are more accessible than private spaces, they afford the potential for observational studies and field-testing of real world applications (Shklovski and Chang, 2006). They also have the capacity to provide a large number of participants for data collection purposes whilst ensuring high ecological validity of the results - the extent to which behaviour observed in an experiment reflects behaviour that occurs in a natural setting.

According to Hazelwood et al. (2008) ambient information systems only function as they are designed to when they are congruent with an observer's everyday environment. Therefore, to be able to test the effect of the ambient displays it was important that the experimental setting replicated, as far as possible, a natural environment which participants might encounter in their everyday lives.

Wisneski et al. (1998) suggested that ambient media are subject to learning effects where familiarity with the environment changes how people engage with them, increasing their facility for using the space. With this in mind, it was important that the setting for the experiments was an established space which had become a familiar environment for the participants.

It was also important for the experiment to exploit the concept of natural physical affordances (Norman, 1988) and provide an environment which facilitated seamless interaction between perceivers, and digitally augmented architectural space.

By using video recording equipment to capture data the role of the experimenter was minimised during the data collection procedure, this reduced the potential for bias introduced by the experimenter's presence and provided a standardised and replicable method with which to record data objectively.

A number of experiments were developed and conducted to test the overarching hypothesis. These are summarised below:

Pilot study

The pilot provided the initial testing ground for the exploration of the influence of digital depth augmentation on people's movement. The study was conducted in public architectural space and involved the manipulation of a digital projection on the wall of a digital art exhibition.

Experiment 1

Experiment 1 examined how people's turn based decisions at a T-junction corridor were influenced when a digital display acting as a virtual window was introduced into the space. The digital screen displayed a live feed from a camera looking into the space behind the corridor. The experiment involved two conditions, where the display was placed either on the right or left of the corridor; the data from these conditions were compared against control data collected when no display was present in the experimental setting.

Experiment 2

In Experiment 2 the digital display was again introduced in the T-shaped corridor, but remained in the central position throughout. As in experiment 1, the digital screen displayed a live feed from a camera looking into the space behind the corridor. The manipulation in Experiment 2 involved digitally altering the vanishing point of the projected image, by altering the position of the camera, so that in a central condition the display acted as an opening in the wall of the corridor but in the left and right conditions the perspective of the image was skewed.

3.2.1 Pilot Study

The pilot study provided an opportunity to explore methodological issues prior to developing the final experimental conditions and procedures for data collection and analysis. The study examined the distribution of people within an architectural space when a digital display was used introduced a perceived curve to a wall.

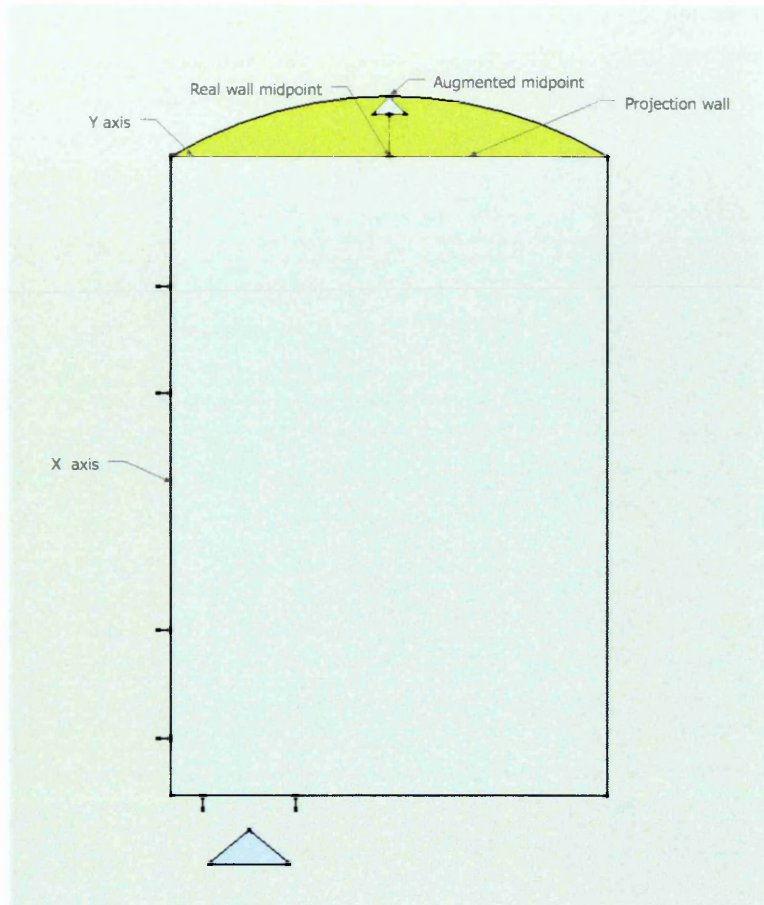


Figure 11. Showing a sketch of the experimental set up for the pilot study.

Three conditions were tested, the first, where no visual-depth augmentation was present and the second and third where visual-depth was manipulated. A video camera recorded the position people were standing in at regular intervals during the three testing periods and this formed the data for the experiment.

Full details of the experimental design and procedure of the pilot study can be found in Chapter 4.

3.2.2 Experiment 1

The pilot study investigated the perception of boundaries in a hybrid system by observing people's use of space. The main experiments introduced a decision making point where participants were required to decide between a left or right turn to proceed through the experimental setting which was designed as a T-shaped corridor. In Experiment 1 a wall mounted ambient display introduced augmented visual-depth by showing a live feed of the space beyond it - or what a participant might expect to see if the digital projection was a window. This was placed in a right or left-hand position in the corridor and people's turn-based decisions were recorded. The digital image provided stable depth information, therefore the experiment was able to isolate the impact of the position of the display on people's movement through the corridor.

A series of tests conducted prior to the commencement of the main experiments were designed to establish two sets of control data. Firstly, in a base-model test participants were observed moving through the corridor when no digital display was present. This test was carried out to establish the natural rate of left-right turn decisions when no manipulation was present. Secondly, three display tests were carried out to examine the influence of the physical display unit and how images providing no visual-depth cues affected participants' behaviour when walking through the corridor.

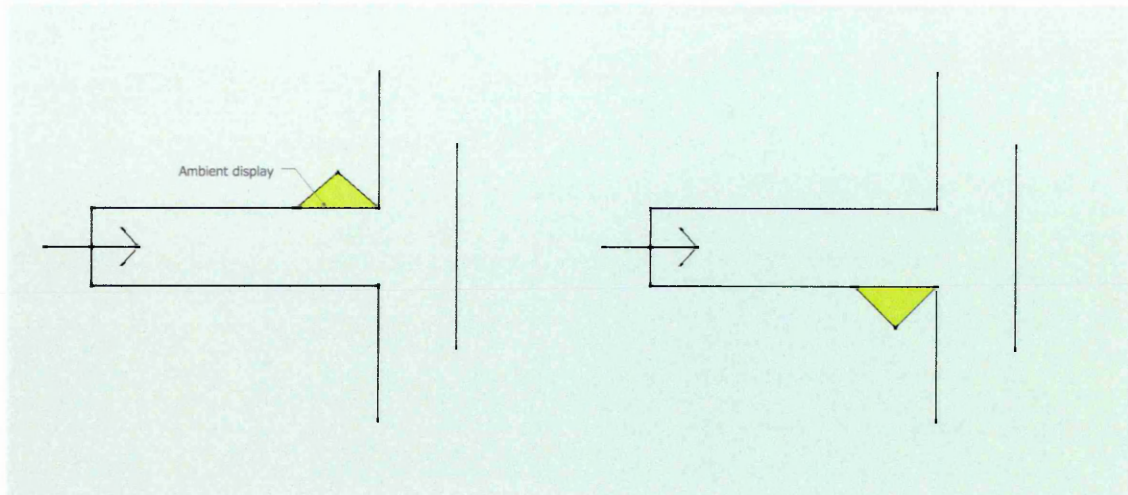


Figure 12. Showing the T-shaped corridor and the positioning of the ambient display in the two experimental conditions.

Full details of the experimental design and procedure of the Experiment 1 can be found in Chapter 5.

3.2.3 Experiment 2

In Experiment 2, people's turn-based decisions were recorded in response to a centrally mounted ambient display providing natural or skewed perspective projections of the space behind the wall. Whilst Experiment 1 tested the effect of position of the augmentation on people's movement, Experiment 2 held the position of the display constant, whilst altering the vanishing point of the displayed image by changing the position of the camera. In the first condition this provided a virtual 'window' perspective – what the participant might expect to see if the display was replaced by a physical window. In the following two conditions the display showed a skewed perspective projection, either left or right.

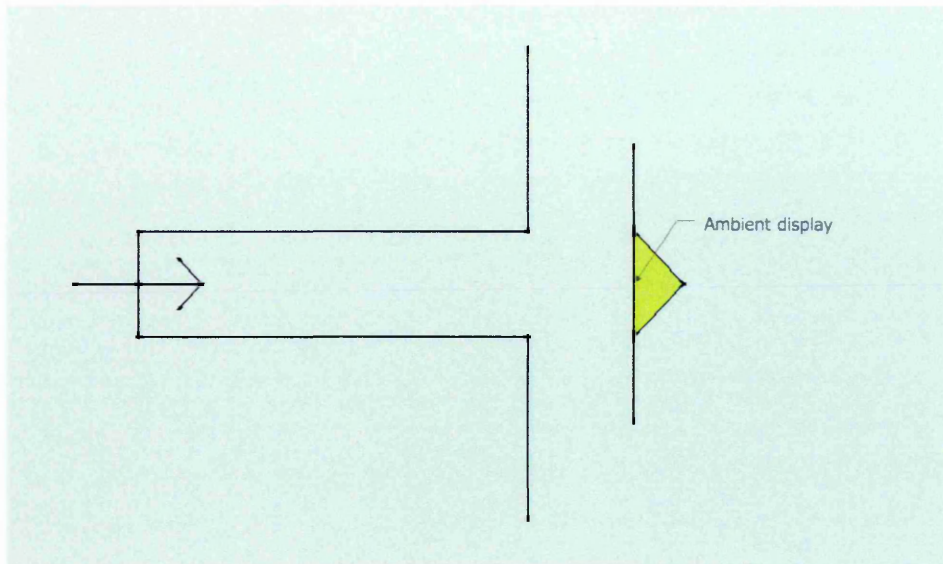


Figure 13. Showing the T-shaped corridor and position of the ambient display in all three conditions of Experiment 2.

Full details of the experimental design and procedure of Experiment 2 can be found in Chapter 5.

3.3 Data collection

The pilot study was set at an interactive digital exhibition in Portugal in which participants actively engaged with the exhibits. The organisers of the exhibition provided permission for the observation of people's movements in response to a manipulation of the perceived curvature of an image projected on a wall of the experimental space. A video camera was used to measure people's positions throughout the experiment.

The main experiments were conducted over a period of several weeks in an artificially designed environment the Ambient Technology Laboratory in the Jenny Lee Building at the Open University in Milton Keynes. Subjects were recruited by an open email invitation and by posters around the building.

3.4 Method for data analysis

3.4.1 Pilot Study

The data for the pilot experiment consisted of a series of distribution figures which described the position of people within the experimental space. The data were recorded as x and y coordinates. The data were analysed by comparing the means of the distributions to see if they were significantly different.

3.4.2 Experiments 1 and 2

The data for the first main experiment consisted of left-right turn decision data for two conditions, compared against base model data recorded when no display was present:

- | | |
|----------------------------------|---|
| 1. Base model (no display): | number of left and right turn decisions |
| 2. Display located on the left: | number of left and right turn decisions |
| 3. Display located on the right: | number of left and right turn decisions |

The data for Experiment 2 was recorded and analysed in the same manner as Experiment 1 and was as follows:

- | | |
|--|---|
| 1. Central vanishing point (virtual window condition): | number of left and right turn decisions |
| 2. Left-skew of image vanishing point: | number of left and right turn decisions |
| 3. Right-skew of image vanishing point: | number of left and right turn decisions |

To control for the potential impact of group factors skewing the data, that is, people moving through the corridor with others and being influenced by their turn decision, the data were analysed in two ways.

- 1) **Individual count data.** Counting each person moving through the corridor as an individual participant providing a data point.
- 2) **Group-factored data.** Counting each participant moving through the corridor *alone* as an individual participant providing a data point. Counting participants moving through the corridor with another person or in a group as a single entity providing a single data point, regardless of the number of participants forming the group.

CHAPTER 4 - PILOT STUDY

4.1 Introduction

4.2 Study design

4.3 Procedure

4.4 Results

4.5 Discussion

Chapter 4 - Pilot study

4.1 Introduction

The purpose of the pilot study was to provide an initial testing ground to explore if and how it was possible to detect an observable change in people's use of space in a simple architectural setting when spatial boundaries were manipulated by the introduction of ambient displays providing augmented visual-depth information.

Whilst it was theoretically possible to base the design of the main experiments on a foundation of current theory and expertise in the field of architecture and space analysis, the pilot study was considered important for the opportunity it provided to observe and assess any methodological issues prior to the main experimental phase and for providing evidence upon which to carry out further experimentation.

4.2 Study design

The pilot study introduced a basic form of visual augmentation in a simple architectural space and formed part of an informal exhibition of digital art in Porto, Portugal. The experiment was set in a room which connected to three other exhibition spaces and acted as a concourse where people socialised and consumed refreshments. The space attracted a high number of visitors throughout the duration of the experiment.

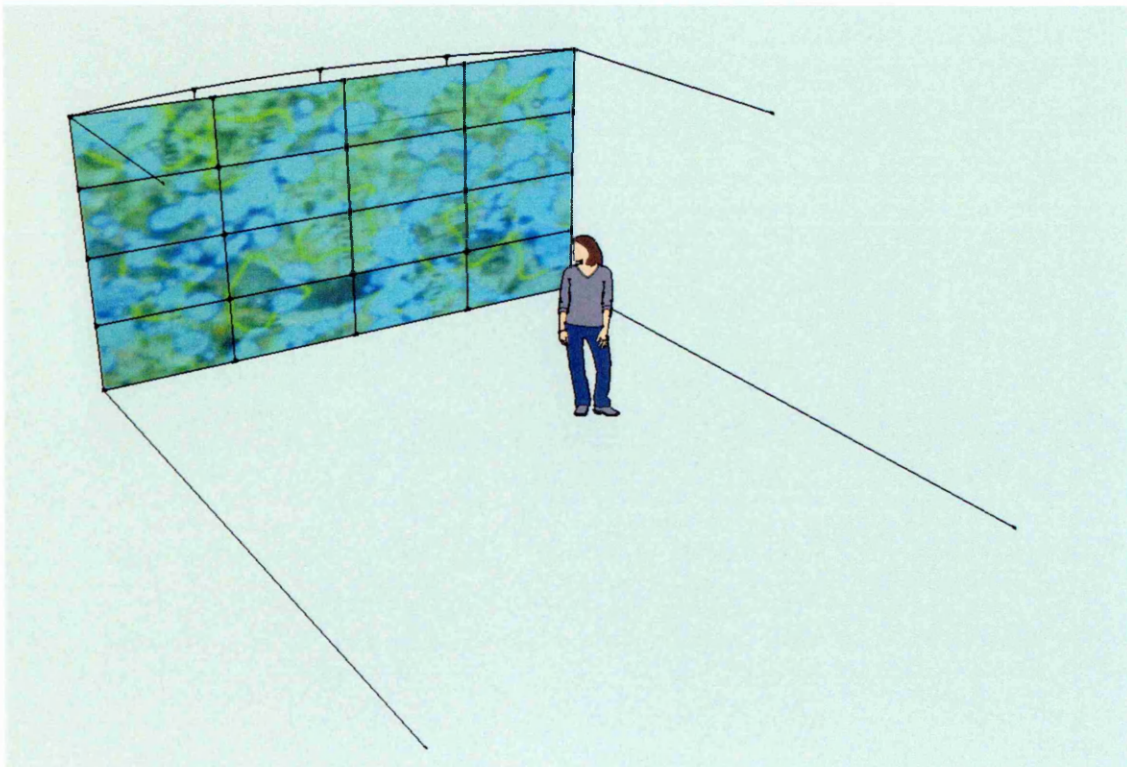


Figure 14. Initial concept for the study design showing the digital projection area in green, and potential visual-depth manipulation through curvature of the image.

The key design components that needed consideration before the implementation of the pilot were:

- Architectural properties of the experimental space
- Visual content of the projection
- Technical components of the experimental set-up
- Data collection procedure

4.2.1 Architectural properties of the experimental space

Walls are the ubiquitous defining feature of our built environment. They delineate structures and act as barriers that limit where we can go and what we can see. The purpose of the experiment was to test, through measuring a change in human behaviour, whether digital augmentation can alter the fundamental aspects of this principal element of architecture by removing the spatial barrier presented by a wall. Therefore, a simple architectural setting was required where the influence of digital augmentation could be measured and confounding variables, the uncontrolled aspects of an experiment which could distort the relationship between the variables under study, could be minimised.

In order to project an image which was capable of altering the visual-depth that participants' perceived the augmented wall needed to be a plain rectangle with no curvature and have sufficient space in front of it to enable a projector to display an image which filled the entirety of the wall. The architectural space needed to be visually unobtrusive in order to provide a neutral experimental setting, and as such a rectangular room was selected with similar walls on each side as shown in Figure 15.

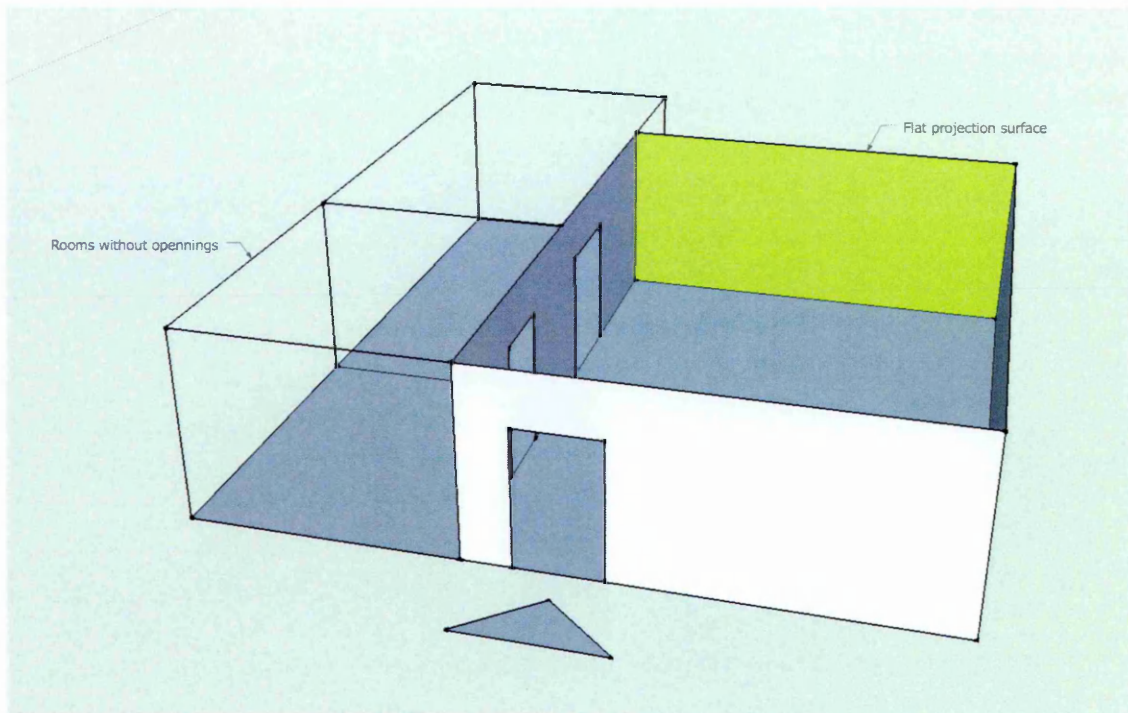


Figure 15. Pilot study setting and projection surface.

4.2.2. Visual content of projection

The content of the projection had to be carefully designed in order to isolate the visual-depth manipulation in the three conditions. To do this an abstract image which contained no depth cues was produced. The image had no perceived central vanishing point and created no augmented depth when projected on to the target wall. To introduce perceived depth in the experimental conditions a 15% or 30% curve was applied to the image by bending the digital projection surface using custom software.

4.2.3 Technical components of the experimental set-up

- **Projector**

A standard definition (800x600 pixel) projector was installed on the ceiling (position shown in Figure 16). The projector was capable of projecting an edge-to-edge image creating a fully digitally-augmented wall. The height that the projector was mounted at minimised, as far as was possible, the possibility of disruptions to the augmentation caused by shadows from participants standing near the projection wall.

- **Fisheye lens camera**

A Fire-I camera with factory 'fisheye' lens was used, connected to a Mac-Mini via firewire.

- **Mac-Mini**

A Mac-Mini, 2008 model, was used to run the custom software designed for the experiment which produced the projection and facilitated data collection via the camera.

4.2.4 Data collection procedures

The camera used to record positions throughout the experiment was installed in the same location as the projector, on the ceiling of the experimental space, at a recording height of 3.5 meters.

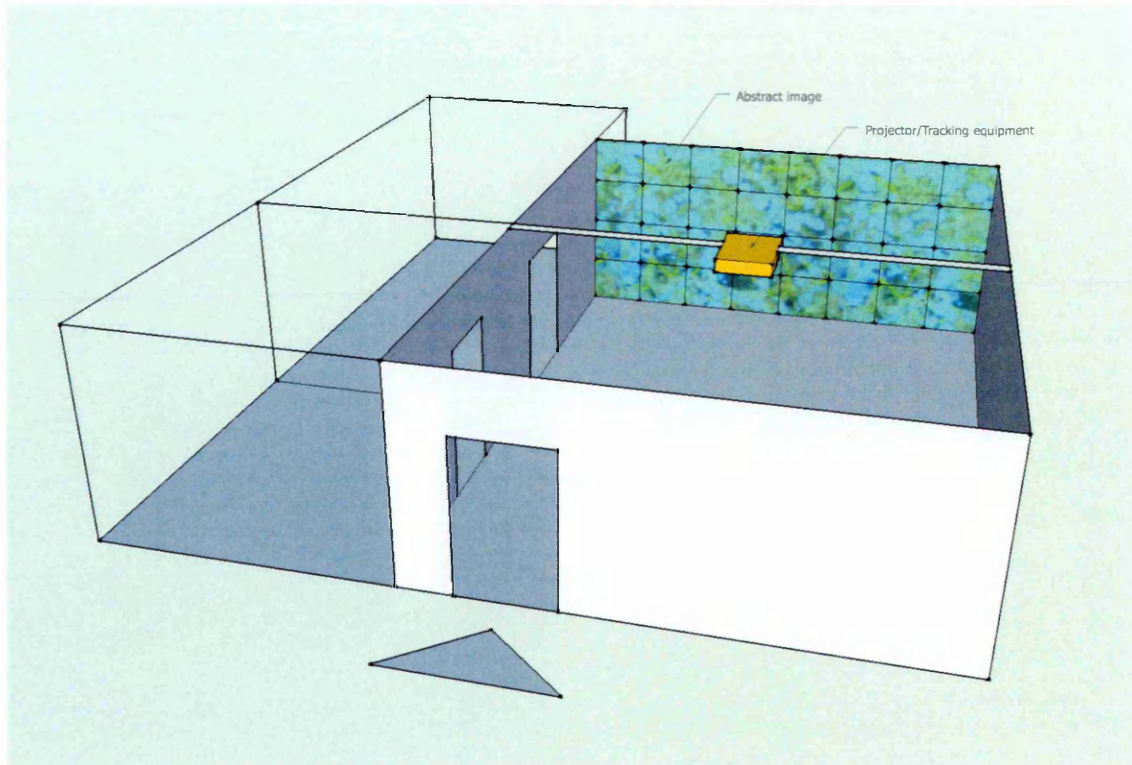


Figure 16. Showing the positioning of the digital projector and tracking equipment during the pilot study

The camera recorded an image of the entire room at three minute intervals throughout the day. The positions of people recorded in these images were recorded as a series of x,y coordinates. The orientation of the axes are shown in Figure 17.

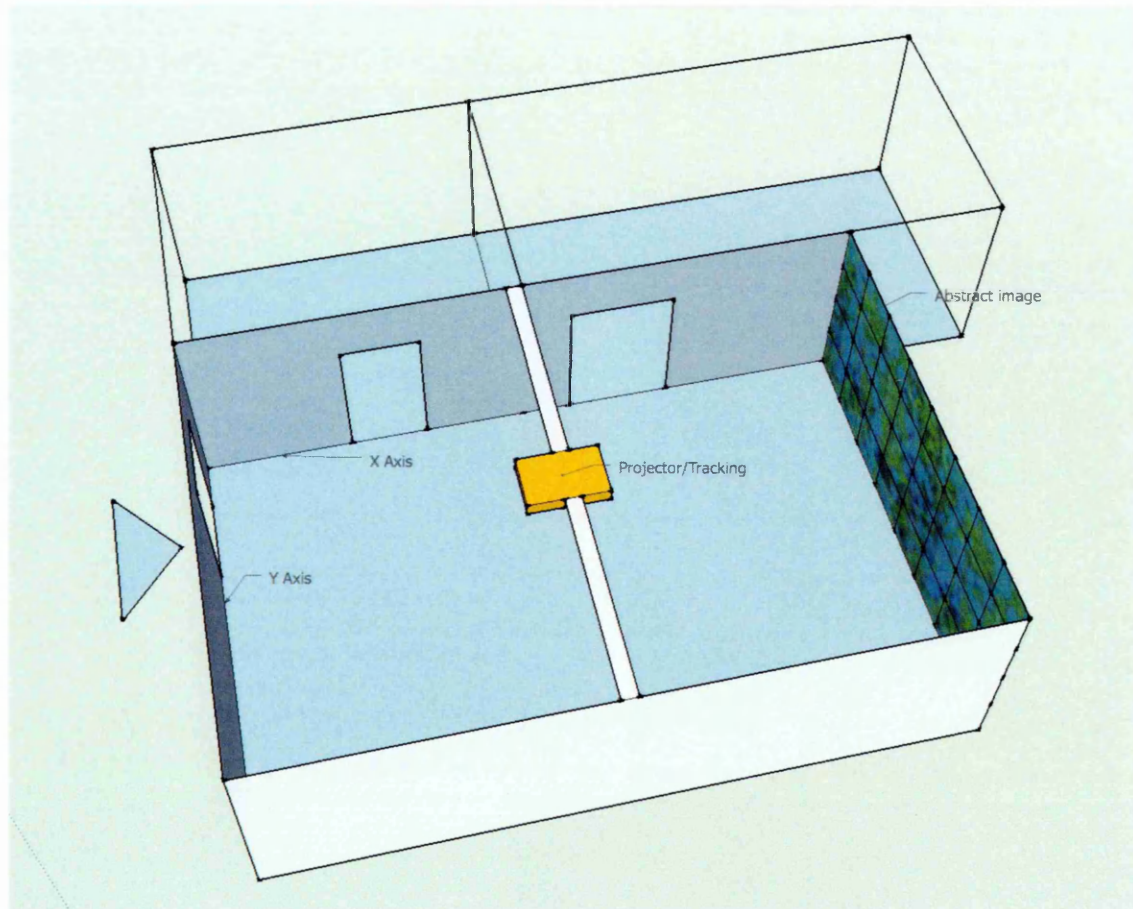


Figure 17. Showing the orientation of the data collection axes in the pilot study setup.

For the data extraction, a 'blob' detection technique was employed, utilising Open Source Computer Vision (OpenCV) algorithms. Counting people multiple times (in multiple three-minute data captures) as well as counting groups of people in close proximity to each other as one data point were considered as acceptable forms of potential data contamination due to the nature of the pilot study investigation.

No original images of the data captures were stored and the final data output consisted of a set of 6744 coordinates over the three conditions.

4.3 Procedure

The study was divided into three phases, each lasting a day.

Phase One

During the initial phase an abstract image was projected flat onto the target wall. This provided an environment in which digital augmentation was present without the manipulation of perceived visual depth and provided an opportunity to record people's use of the space under control conditions (Figure 18).

The fisheye camera recorded the locations of people throughout the day at three minute intervals and the data output consisted of around 180 images of the x,y coordinates of individuals throughout the day. From the 180 images, 2200 sets of coordinates were extracted.

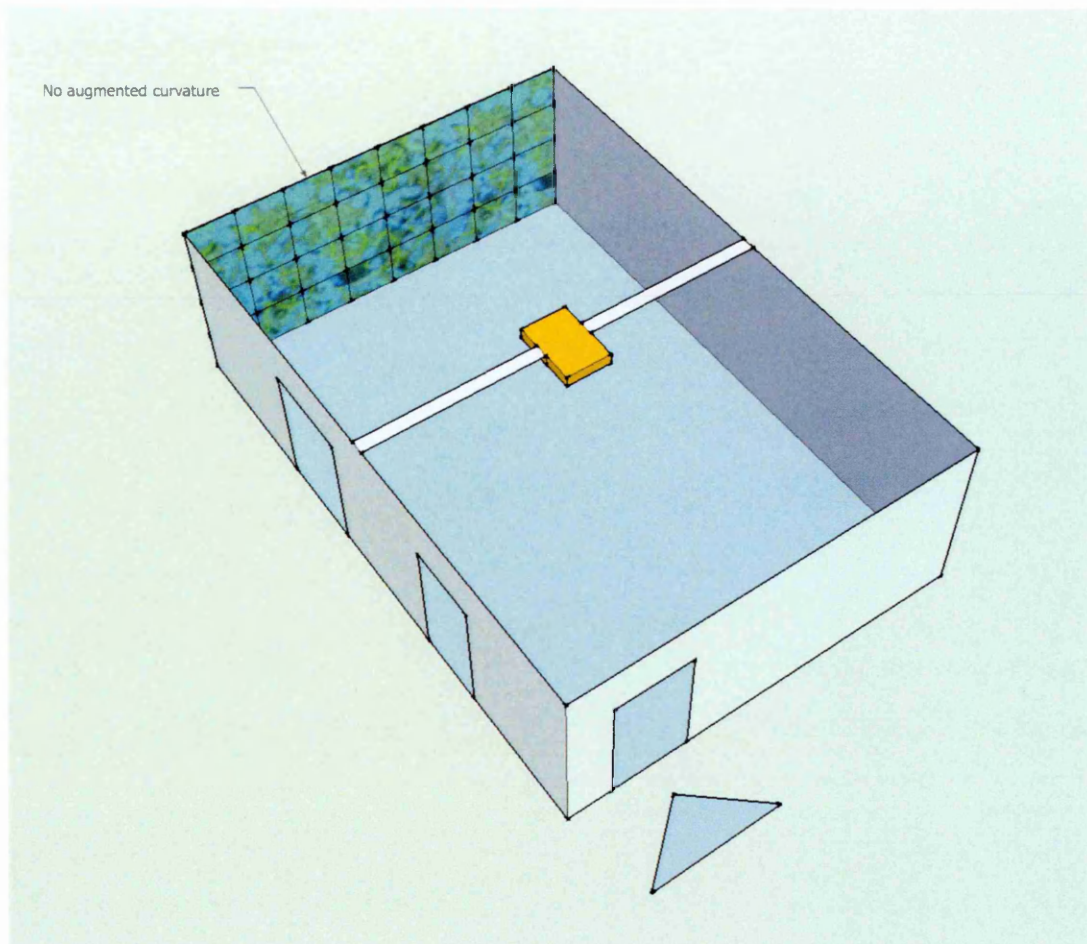


Figure 18. Showing the experimental set-up during phase one of the pilot study.

Phase Two

During the second phase of the study the projector displayed the abstract image but with the introduction of visual-depth cues. The four corners of the projected image were aligned with the physical architectural corners, however the middle of the image digitally augmented the physical wall by appearing to 'push it back' creating a curve

in the wall. This was achieved by using the software to bend the virtual projection surface. Figure 19 depicts the wall's real midpoint and augmented midpoint.

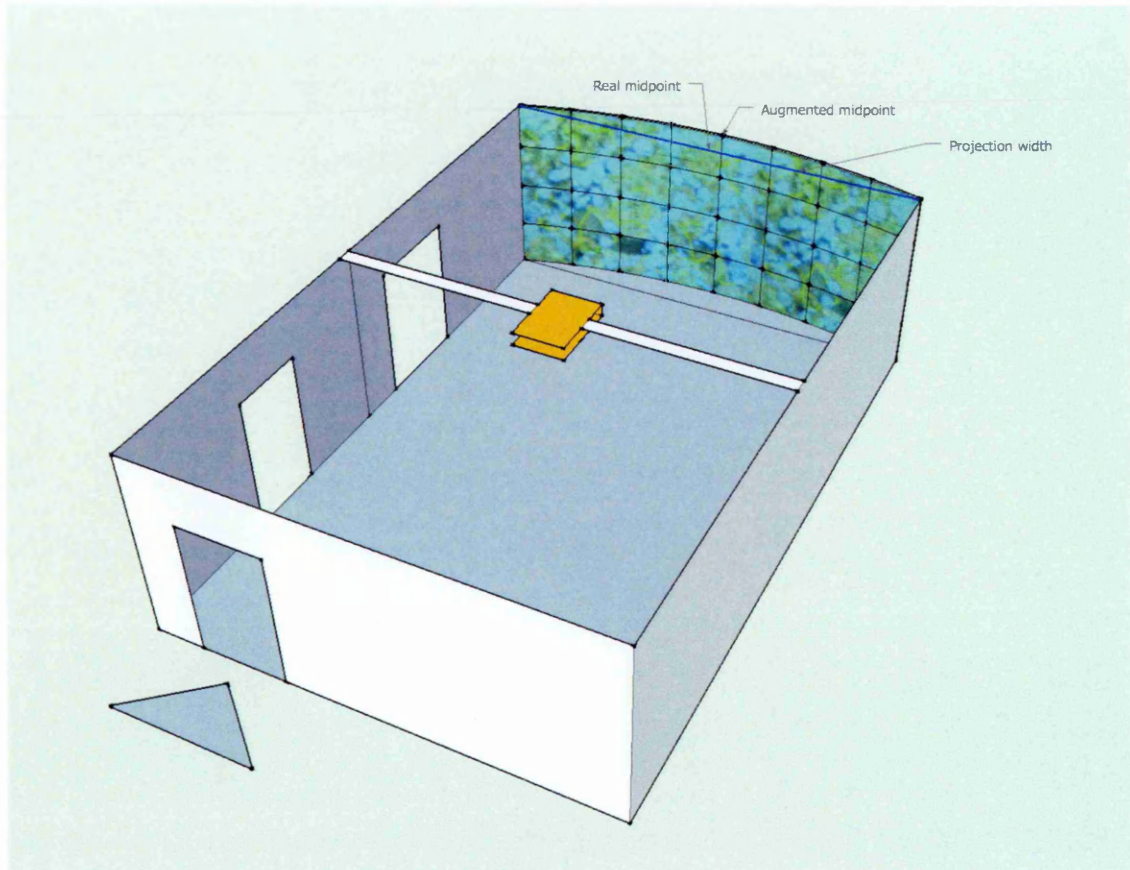


Figure 19. The experimental set-up in phase two of the pilot study, showing a 15% curve at the midpoint of the projected image

During the second phase the augmented midpoint of the projection was set to a value of 15%. That is, the virtual depth created between 'real midpoint' of the wall and 'augmented midpoint' of the wall was 15% of the width of the projection.

The fisheye camera recorded locations of people throughout the day at three minute intervals and the data output consisted of around 180 data captures throughout the day. From the 180 images, 2379 sets of coordinates were extracted.

Phase Three

In the final phase of the pilot study an image was displayed which digitally augmented the wall of experimental space with a curve of 30% of the width of the projection. This provided an image with twice as much curvature as that displayed in phase two of the pilot (Figure 20).

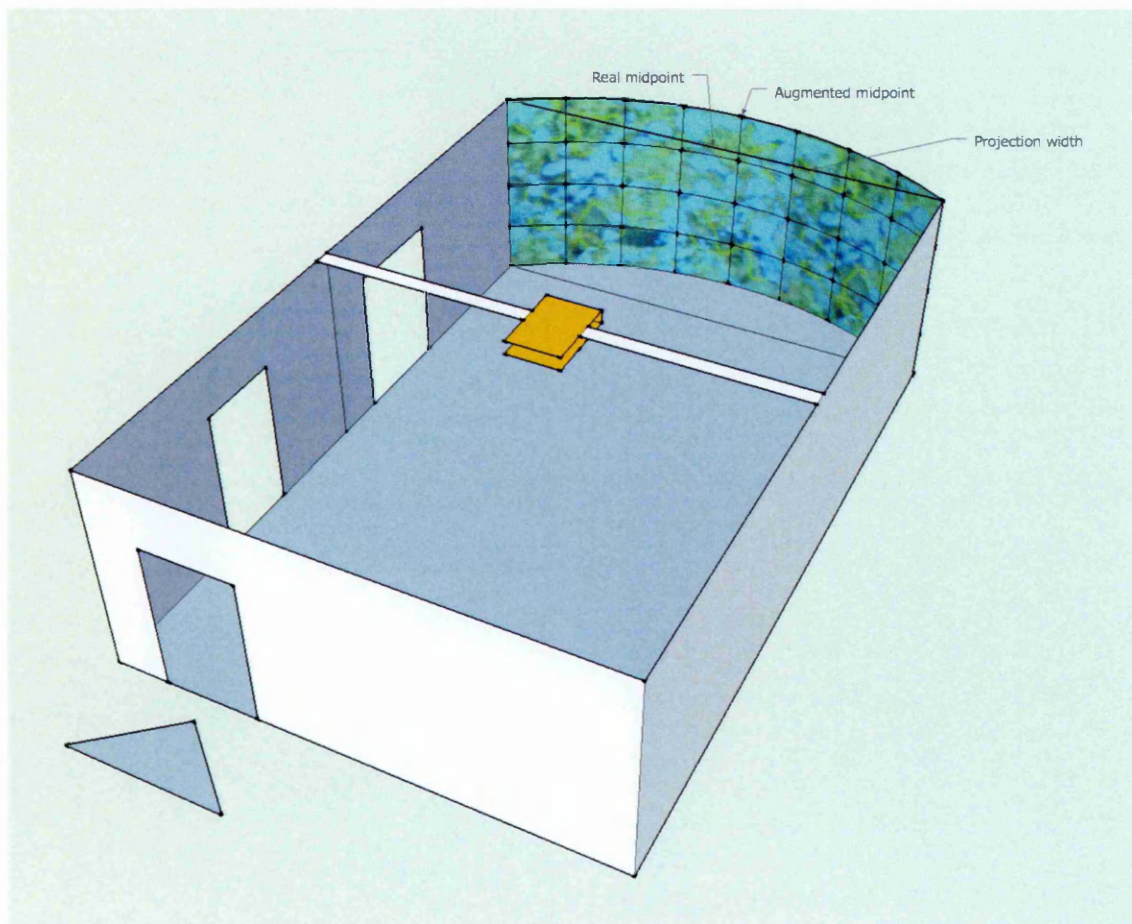


Figure 20. Showing the experimental set-up during phase three of the pilot study, with a 30% curve at the midpoint of the projected image.

The fisheye camera recorded locations of people throughout the day at three minute intervals and the data output consisted of around 180 images throughout the day. From the 180 images, 2165 sets of coordinates were extracted.

Data analysis procedure

At the end of data collection period, three files containing x,y figures describing the position of participants during the three phases of the study were produced.

The scale of the axes was produced by numbering the pixels in the recording equipment's digital frame, starting at $x=0, y=0$ at the upper-left corner of the room. The limit in the x axis was 1024 pixels and in y axis, 768. The digitally augmented wall was positioned on the right hand side of the room starting at location $x=1024,y=0$ and ending at $x=1024,y=768$. Each individual location was added and the total was divided by the total number of locations tracked during the day.

The data were subjected to analysis conducted with JMP to detect any differences between the data from the three phases.

4.4 Results

Descriptive results for the pilot study are shown in Table 1.

	Number	Mean x	Standard deviation	Standard error mean	Lower 95%	Upper 95%
Phase 1	2200	455.4	238.7	5.1	445.4	465.4
Phase 2	2379	471.4	255.3	5.2	461.1	481.7
Phase 3	2165	495.9	251.1	5.4	485.3	506.4

Table 1. Descriptive results of the pilot study.

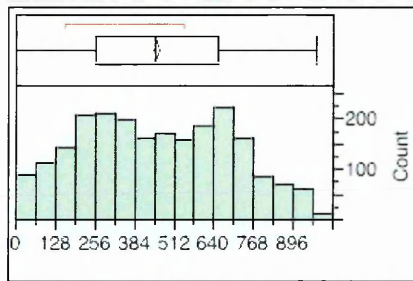
The data shows that during the first phase of the study, the coordinate of the mean location of the participants during the day was $x=455$, $y=286$. The data collection from the first day provided information to form the base model for comparison with the results of phase two and three of the pilot study, providing a control in which a digital image, but no depth augmentation was present.

The results from the second phase of the study, during which a perceived 15% curvature of the wall was introduced through digital augmentation, showed that the mean of the x axis figure for participants throughout increased, with a shift in location of 16 pixels towards the digitally augmented wall. There was an insignificant change in the mean of the y axis score at 283.

During the third phase of the study, in which the digitally augmented wall displayed 30% curvature the mean value for the location of people on the x axis was 495, a 40 pixel increase from the day one control showing a shift towards the digitally augmented wall. The mean score for the y axis was 292 pixels.

Pilot - Day 1 - No Augmentation

Pixels (x) - Higher is Closer

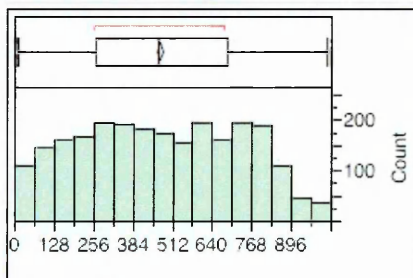


Summary Statistics

Mean	455.39909
Std Dev	238.72851
Std Err Mean	5.0897088
Upper 95% Mean	465.38023
Lower 95% Mean	445.41795
N	2200

Pilot - Day 2 - Augmentation 15% of 'wall width'

Pixels (x) - Higher is Closer

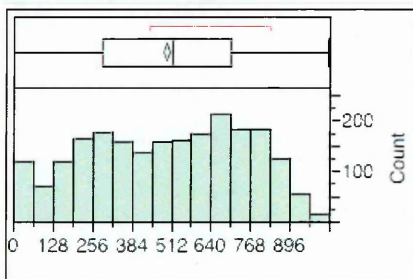


Summary Statistics

Mean	471.39765
Std Dev	255.34281
Std Err Mean	5.2351172
Upper 95% Mean	481.66351
Lower 95% Mean	461.13178
N	2379

Pilot - Day 3 - Augmentation 30% of 'wall width'

Pixels (x) - Higher is Closer



Summary Statistics

Mean	495.85497
Std Dev	251.12463
Std Err Mean	5.3970987
Upper 95% Mean	506.439
Lower 95% Mean	485.27093
N	2165

Figure 21. Data outputs of the three phases.

Pilot Study

Mean(Pixels (x) - Higher is Closer) vs. Day of Pilot Study

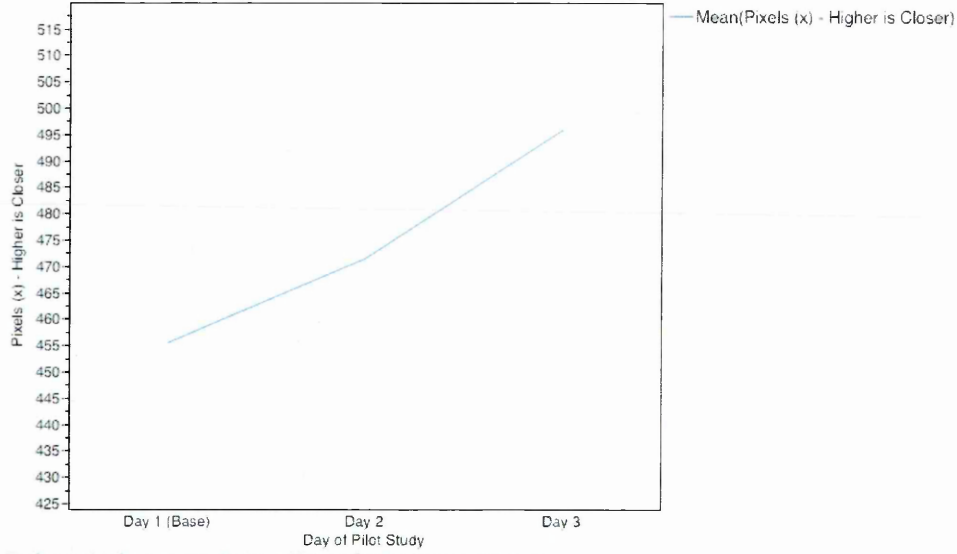


Figure 22. Showing the mean position of participants during the three phases of the pilot study.

4.5 Discussion

The data from the experiments show that there was an upward trend in the figures recorded for the *x* axis locations during the three phases of the experiment, whilst no such trend was observable in the *y* axis scores. The increase in *x* axis scores represents a shift towards the digitally augmented wall in the experimental setting.

The results show that people's distribution in space was different during the three conditions, when the physical architecture was digitally augmented to extend the visual depth that people perceived. There was also evidence to suggest that as the visual-depth of the augmented wall was increased there was an increased likelihood of people occupying space closer to the augmented wall. The findings support the hypothesis and suggest that people's perception of physical architectural boundaries can be manipulated by introducing digitally augmented visual depth and their behaviour can be influenced by this.

The results of the pilot study were encouraging, however, the opportunistic nature of the study meant that some aspects of the study were uncontrolled and caution is required when interpreting the results. For example, the data collection procedure was not sensitive to the possibility of one participant providing numerous data points, by remaining in the room for multiple data captures (at three minute intervals), and this may skew the results of the experiments. In addition, the setting of the experiment, in a pre-existing public architectural space meant that the structure of

the room was uncontrolled and aspects of its design may have influenced people's use of space in a way which the pilot could not account for, for example, the position of the entry and exit points in the space were unsymmetrical.

However, despite these cautions, by demonstrating that the chosen methodology was able to detect a change in behaviour, which when viewed in light of the hypothesis of the study suggests the impact of virtual-depth on human behaviour, the pilot study provides evidence and confidence upon which to develop further experiments to test the phenomenon.

CHAPTER 5 - MAIN EXPERIMENTS

5.1 Introduction

5.2 Experimental design

5.3 Base model and display
testing

5.4 Experiment 1

5.5 Experiment 2

Chapter 5 - Main Experiments

5.1 Introduction

The results of the pilot study suggested that the methods used were successful in manipulating the augmented visibility of an architectural space, and that people's use of space changed when this manipulation occurred. This is significant because, as shown by the literature review, current theories of space analysis, such as space syntax, cannot account for the influence of visual-depth augmentation caused by the introduction of an ambient display. Therefore, according to the current theory the presence of the digital display should not influence people's use of space. In light of the limitations of current theory and the findings of the pilot study, the aim of the main testing phase was to further develop the testing of visual-depth manipulation on behaviour and carry out this testing in more controlled experimental conditions.

Two experiments were developed to observe and analyse people's use of space in a variety of augmented visual-depth conditions. These experiments explored how people's movement patterns could be influenced through the use of embedded digital technologies in more complex architectural space and introduced a measurable behavioural outcome in the form of a left or right hand turn that participants were required to make when proceeding through the experimental

space, designed as a T-shaped corridor with a target area beyond. The design of the environment for these experiments was influenced by both the research question and evidence that resulted from the pilot study.

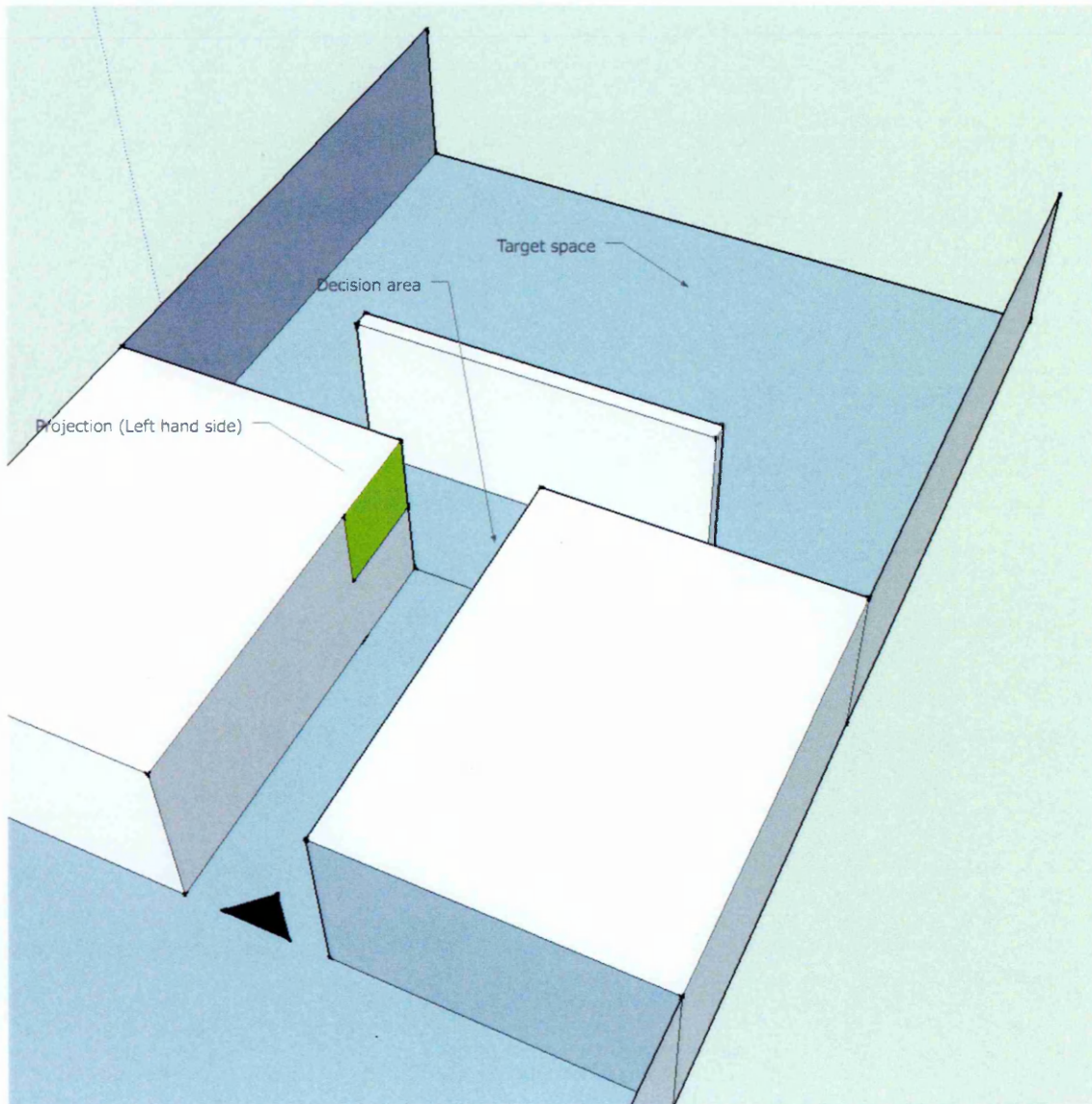


Figure 23. Showing the design of the experimental space for the main experiments with the projection in the left-hand position.

The experiments were set in an enclosed public architectural space designed specifically for the purpose. The public nature of the space provided an opportunity

to observe and analyse people's movement in a natural setting and provided a large and ecologically valid sample from which to collect data.

In this experimental space both routes through the T-shaped corridor to the target space are equidistant and identical. The theoretical assumption of space syntax theory is that the flow of participants' movement would be split roughly 50/50 along the two routes. This is because the isovist shape is identical on either side of the T-shaped corridor. More specifically, following Turner's (2003) hypothesis an agent faced with a decision point would walk towards the space that affords the possibility for a further destination. As the geometry of the space is symmetrical both paths afford the same possibilities and therefore the probability of moving right or left at the junction should be exactly the same. Therefore the experiment is able to test for any change in the relative magnitude of pedestrian flows in this setting because of the introduction of digital-depth manipulation.

In contrast to the current theory, the hypothesis of the experiments was that changes in movement patterns would be observable when static architectural space was digitally manipulated to alter participants' perceived visual-depth.

5.2 Experimental design

5.2.1 Setting

The requirements of the experimental setting were carefully considered. Having decided upon a measurable outcome of a left or right turn decision it was necessary that the space lent itself to a simple examination of the flow and direction of people through two discrete routes, for example, a corridor or foyer. Therefore, the space required a single entry point and single exit point.

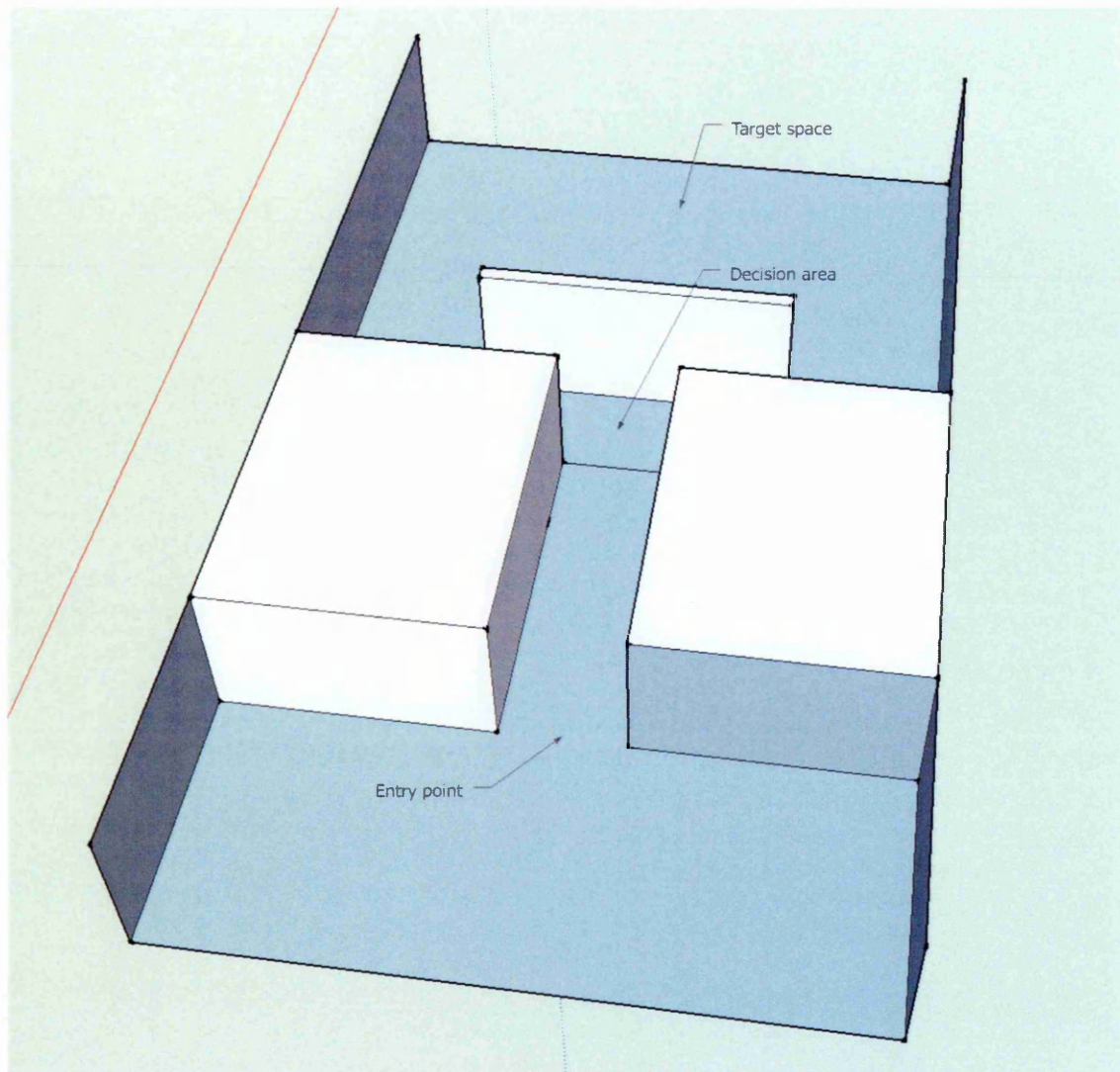


Figure 24. Showing the layout of the experimental space for the main experiments.

To ensure an adequate number of participants used the corridor throughout the testing period it was important that the experimental space was near a focal point or 'target space' with high use. As such, an area such as a common room, or recreational area providing refreshments was considered as a useful target for the corridor to provide access to.

With these considerations in mind the T-shape corridor design was developed where the cross of the T formed a junction at which participant were required to make a turn-decision in order to access the 'target space' beyond the corridor which contained seating, complimentary drink making facilities, and the exit point. The turn-decision required at the T-junction formed the measurable outcome for both of the main experiments.

In order to minimise the effects of confounding variables influencing the behaviour of participants, the T-shaped corridor was designed to be spatially and visually symmetrical. The design was processed in depthmapX version 0.19b (Varoudis, 2012a) (see Figure 25) to create a visibility graph in order to measure and exclude any hidden attributes that might influence the physical symmetry of the layout.

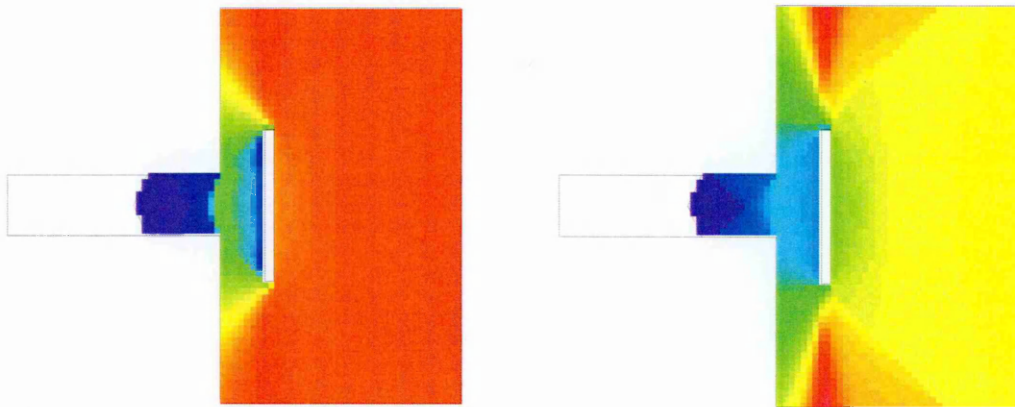


Figure 25. Visibility graph of the experimental space (Connectivity and Visual Integration HH, Red = High, Blue = Low)

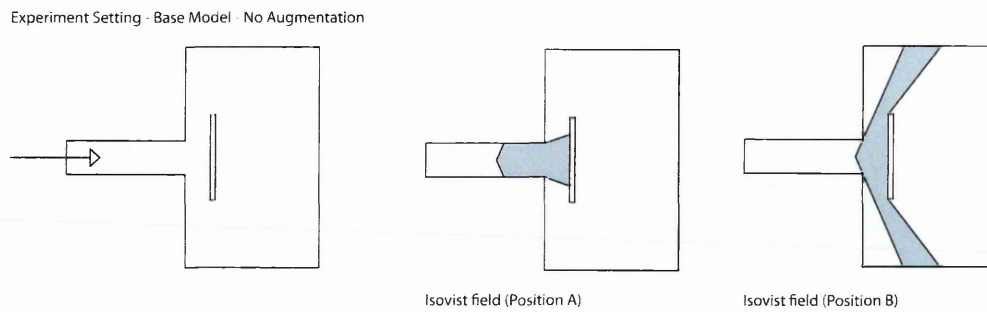


Figure 26 Visibility / Isovists at experimental setting – base model.

5.2.2 Experiment site and build design

With the design of the experimental space fully considered, the corridor was constructed in a suitable environment. The selected space for the experiment was in the Ambient Technology Laboratory located within the Jenny Lee Building of the Open University in Milton Keynes. The laboratory provided a space of approximately 144m² and had no internal walls. Lightweight solid partitions were used to construct the experimental space, these partitions reached the full height of the room. The T-Junction of the corridor led to the target space which was set up as a small cafeteria. This space was designed to provide a casual recreational space where people could socialise and use the complimentary drink making facilities which were available throughout the duration of the experiment between the hours of 8.00am and 6.00pm daily.

5.2.3 Digital display

A Panasonic HD LCD monitor measuring 50 inches was selected to provide the display in the experiments. The display screen had a 15mm black casing which was visible to participants. During the testing phase the screen was linked to a professional Sony HD 3CCD camera positioned to record the target area. The camera recorded in Full HD definition (1920x1200 pixels).

The main function of the display was to act as a live video link providing a one-way feed from the 'target space', introducing the visual-depth manipulation into the experiment. In addition, a series of display and image tests were developed prior to the commencement of the experiment. These tests were designed to assess the influence of the presence of the ambient display when it displayed no depth information. The tests included, 'no content' (display turned off), 'random static images' and 'random animated content'. The null-tests were critical for establishing the influence of the presence of the display and content containing no visual-depth information.

5.2.4 Video installation and data collection

Video recording equipment was installed in the experimental space to provide a synchronised recording of every area in the laboratory. The cameras were installed on the ceiling and configured to track multiple angles, covering the T-junction decision point, the corridor, and the target area. Throughout the duration of the experiment eight video streams were recorded between the hours of 08:00 and

18:00 when the experimental space was accessible. The testing phase was completed over several months.

The cameras were able to focus on participants' faces as they passed through the experiment in order to recognise the participants' sight lines as they approached and moved through the T-junction decision point.

5.2.5 Participants

The participants in the experiment were employees or students working at the Open University and visitors to the building. Over 1300 participants entered the experimental space during the course of the experiment.

The experimental space was clearly marked with signs which informed people approaching that upon entering the corridor they would be participating in an experiment and they would be recorded by video camera. The participants were not made aware of the nature of the research.

Participants entering into the laboratory were directed with a sign to enter the experimental space via the trunk of the T-Junction corridor and exit via a door at the other end of the space in order to avoid two-way traffic in the experimental space.

Email invitations were sent out to the employees and students of the university. These requested that participants visit the experiment, advertised the refreshments available and informed people about what they would be required to do. The emails also informed the participants that the purpose of the experiment would be disclosed

after the data collection phase had been completed. In addition, posters advertising the experiment were placed at key focal points of the building.

5.2.6 Data collection and analysis

The decision that participants made at the T-junction in the experimental area formed the measureable outcome. This data was recorded by reviewing the video footage of the T-junction and noting the outcome. Data for all the participants was recorded in two ways:

- 1) **Individuals.** Counting each person moving through the corridor as an individual participant providing a data point.
- 2) **Groups.** Counting each participant moving through the corridor *alone* as an individual participant providing a data point. Counting participants moving through the corridor with another person or in a group as making a single decision providing a single data point, regardless of the number of participants forming the group.

By recording the data in this manner the data analysis was able to take into account potential confounding variables caused by group influence upon decision making. These data generated by participants' turn-based decision were analysed using a chi-squared test and logistic regression analysis (binomial).

5.3 Base model and display testing

5.3.1 Procedure

Prior to the commencement of Experiments 1 and 2, a base model test and series of display tests were conducted to provide control data.

Base model testing

The first phase of data collection was to gather information about people's movement within the experimental space when no ambient display was present. This 'base model' test was conducted to assess the natural ratio of left and right-hand turn decisions with which to compare the experimental data from the experiments.



Figure 27. Showing the experimental space with display present on the left, a participant walking through the corridor, and an image of the data capture from recording equipment.

The data were recorded over a period of four weeks during which no display was present but the experimental and target area were fully constructed and operational. The number of people passing through the corridor and their turn decision was recorded and the data were subjected to analysis.

Display testing

Three tests were carried out to examine whether the presence of the display device was responsible for any observable behavioural change when it was turned off and when it displayed images containing no visual-depth information.

The tests were as follows:

Device test – the device remained in the experimental position, in the left, right or centre, but the display was turned off for the duration of the test.

Static image test – the device remained in the experimental condition placed on the left, right or centre wall but projected content static images which were selected to be free from any visual-depth cues.

Moving image test - the device remained in the experimental condition placed on the left, right or centre wall but projected moving animated images which were selected to be free from any visual-depth cues.

5.3.2 Results

The results of the base model test and display tests are shown in Tables 2 to 5.

Base model – no display				
	Left turn (count)	Left turn (%)	Right Turn (count)	Right turn (%)
Individual count data	120	55.05	98	44.95
Group factored data	101	54.89	83	45.11

Table 2. Showing the percentage of left and right hand turns in the base-model conditions

Display off test

	Base model	Centre	Left	Right	Totals
Left turn	120 (55.05)	30 (56.6)	45 (52.94)	39 (53.42)	
Right turn	98 (44.95)	23 (43.4)	40 (47.06)	34 (46.58)	
Total turns	218	53	85	73	

Table 3. Showing the count and percentage (%) of left and right hand turns during display test one – display off – with base model data included for comparison.

Static image test

	Base model	Centre	Left	Right	Total turns
Left turn	120 (55.05)	39 (53.42)	40 (57.97)	27 (57.45)	226
Right turn	98 (44.95)	34 (46.58)	29 (42.03)	20 (42.55)	181
Total turns	218	73	69	47	407

Table 4. Showing the count and percentage (%) of left and right hand turns during display test two – static image – with base model data included for comparison.

Animated image test

	Base model	Centre	Left	Right	Totals
Left turn	120 (55.05)	42 (53.85)	34 (53.13)	42 (54.55)	238
Right turn	98 (44.95)	36 (46.15)	30 (46.88)	35 (45.45)	199
Total turns	218	78	64	77	437

Table 5. Showing the count and percentage (%) of left and right hand turns during display test one – animated image – with base model data included for comparison.

Tables 6 and 7 provide comparisons between the left and right turn decisions in the base and display conditions. The first shows data where the display was situated centrally in the corridor; the second shows the results of situating the display in the left and right hand positions. Chi-square testing was carried out on the data shown in the tables and the results are shown below.

		Base model	Display off	Static image	Animation	Totals
Left turn	Count	120	30	39	42	231
	Percentage	55.05	56.6	53.42	53.85	
Right turn	Count	98	23	34	36	191
	Percentage	44.95	43.4)	46.58	46.15	
Total turn count		218	53	73	78	422

Table 6. Showing count and percentage (%) of left and right hand turns during base model and display testing (in central position)

A Chi-square test showed that there was no significant difference in the frequency of turn decisions in the conditions, $X^2(3, N = 422) = 0.16, p = .98$.

		Base	Position – display off		Position – static image		Position – animated image		Totals
			Left	Right	Left	Right	Left	Right	
Left turn	Count	120	45	39	40	27	34	42	347
	Percentage	55.05	52.94	53.42	57.97	57.45	53.13	54.55	
Right turn	Count	98	40	34	29	20	30	35	286
	Percentage	44.95	47.06	46.58	42.03	42.55	46.88	45.45	
Total turn count		218	85	73	69	47	64	77	633

Table 7. Showing the left and right turn decisions in the display tests with base model data included for comparison.

A Chi-square test showed that there was no significant difference in the frequency of turn decisions in the conditions, $X^2(6, N = 633) = 0.67, p = .99$.

5.3.3 Discussion

The results of the base model test suggest that participants show slight bias towards a left turn decision. This was despite the experimental conditions providing a

symmetrical space with no cues with which to bias participants' decisions. Having identified the left bias the base model can account for its presence.

The results for the display tests suggest that the left-hand bias observed in the base model testing continued to be present under the display test conditions. The results of these tests showed that there was no significant difference between the percentage of left and right turns during the base model test (when no display was present) and all of the three display tests.

The initial display test showed that the presence of the physical display unit did not influence people's turn based decision. The further two content tests showed that images which provided no depth information, both static and moving, did not alter people's turn-based decision.

As such, it is established that neither the presence of the physical display, or digital content which does not provide depth cues, have a significant impact upon the turn-based decisions of participants moving through the T-junction corridor. This is a key finding for the research because it demonstrates that these factors do not influence behaviour, and therefore any observable change in turn decision during the testing phases of Experiments 1 and 2 are due to the manipulation of the visual-depth information provided by the digital displays.

5.4 Experiment 1

5.4.1 Hypothesis

The location of a digital display, which augments physical space by introducing augmented depth information, will influence how people move through a T-shaped corridor.

Using a wall mounted ambient display to show an image of a real or virtual space beyond a wall augments the depth of the visual field, influences the topological and visual relations between spaces and as a result, influences people's perception of space and their behaviour.

5.4.2 Procedure

To examine the hypothesis two conditions were tested. In these the digital display acted as a virtual window between the experimental area and target area providing a live video feed of target area to the participant in the corridor.

- In condition one the display was placed in the left hand position.
- In condition two the display was placed in the right hand position.

The position of the display, the camera's field of view and the orientation of the virtual element for the conditions tested in Experiment 1 are shown in Figures 28 and 29.

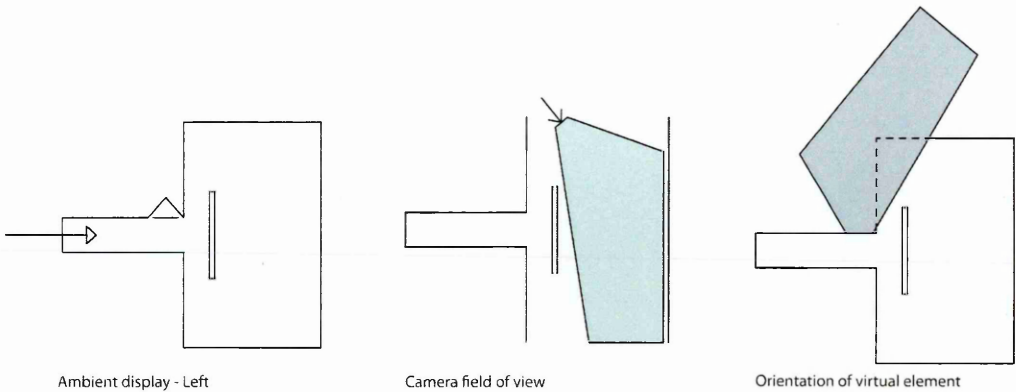


Figure 28. Showing the experimental setup for the left-hand condition

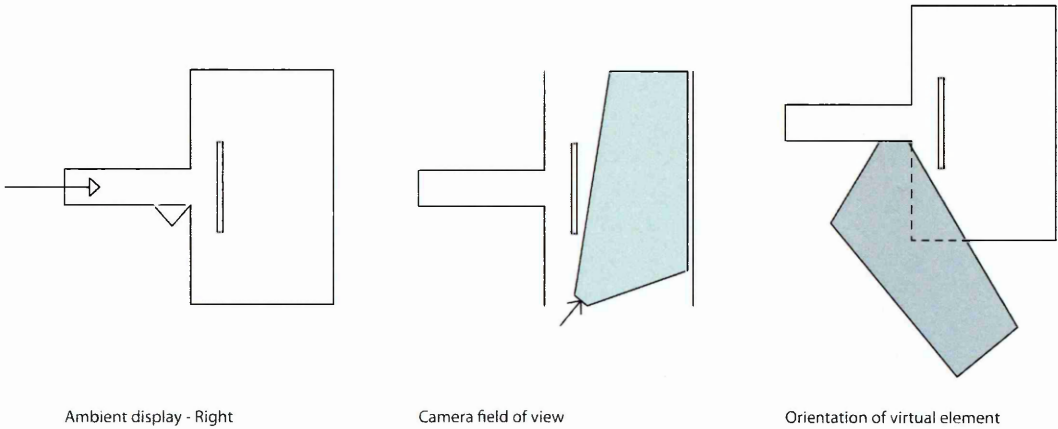


Figure 29. Showing the experimental setup for the right-hand condition

Figure 30 shows a participant moving through the experimental space with the display placed in the right hand condition and figure 31 depicts a computer generation recreation of the visual experience of the participants during the experiment (right condition).

Figure 30. Showing a participant moving through the corridor in the right hand side condition

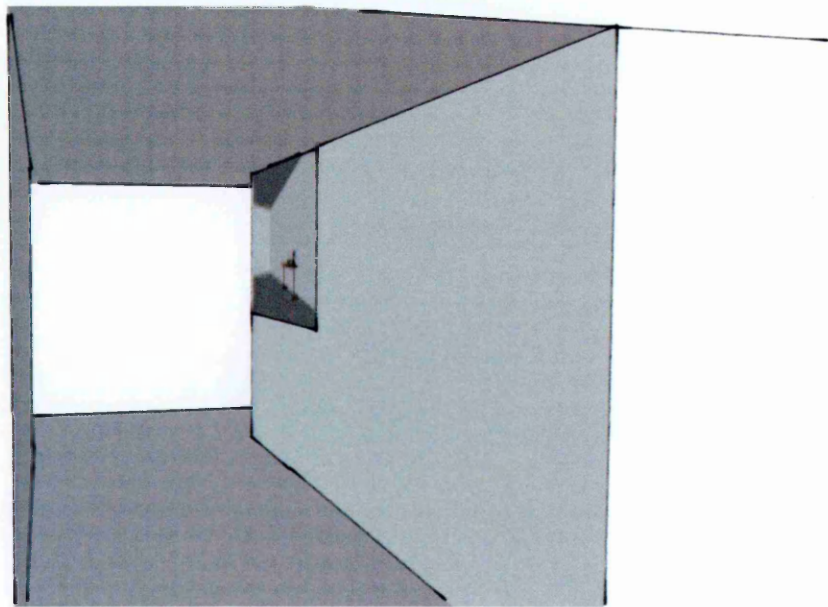


Figure 31 Computer generation recreation of the visual experience of the participants during the experiment (right condition)



5.4.3 Results

The results of Experiment One, and base model data for comparison, are shown in Table 8.

	Condition	Left turn (count)	Right turn (count)	Left turn (%)	Right turn (%)
Individual count data	Base data	120	98	55.05	44.95
	Right hand side	56	80	41.18	58.82
	Left hand side	79	29	73.15	26.85
Group- factored data	Base data	101	83	54.89	45.11
	Right hand side	49	67	42.24	57.76
	Left hand side	50	25	66.67	33.33

Table 8. Results from Experiment 1 compared with base model data.

To test the significance of the results from the three unmatched groups, a Chi-square testing was conducted. Table 9 provides the results of the analysis of 'Individuals' data - counting each person moving through the corridor as an individual participant providing a data point. Table 10 provides 'Group' data - counting each participant moving through the corridor alone as an individual participant providing a data point and counting participants moving through the corridor with another person or in a group as a single data point.

	Base	Left	Right	Total
Left turn	120 (55.05)	79 (73.15)	56 (41.18)	255
Right turn	98 (44.95)	29 (26.85)	80 (58.82)	207
	218	108	136	462

Table 9. Show the results of a Chi Square test conducted on individual count data

A Chi-square test on the data showed that there was a significant difference in the frequency of turn decisions in the conditions, $X^2(2, N = 462) = 24.89, p < .001$.

	Base	Left	Right	Total
Left turn	101 (54.89)	50 (66.67)	49 (42.24)	200
Right turn	83 (45.11)	25 (33.33)	67 (57.76)	175
	184	75	116	375

Table 10. Show the results of a Chi-Square test conducted on grouped data

A Chi-square test on the data showed that there was a significant difference in the frequency of turn decisions in the conditions, $X^2(2, N = 375) = 11.27, p = .004$.

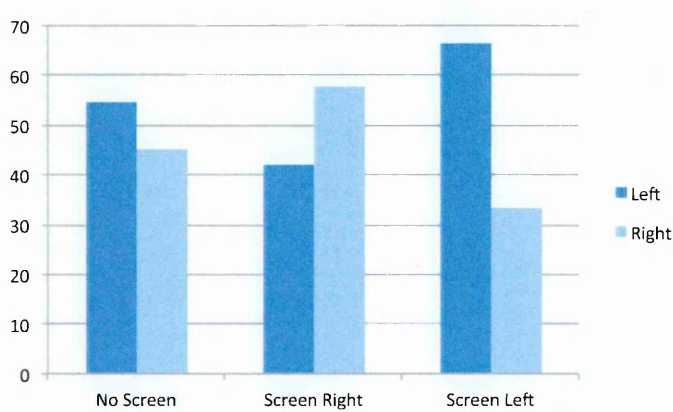
Both of the p-values from the Chi-square analysis showed that there was a significant difference in the turn based decisions in the different conditions. The trend in the results can be clearly observed in the data. In the phase where the display was located on the right side, the distribution of turn decisions was 41.2% turning left and 58.8% turning right for the individual count data and 42.2% left and 57.8% right for the group-factored data, showing a clear difference in the turn-based decisions.

The shift towards right turn decisions from the base data was more than 13% for the individual count data and more than 12% for the group-factored data.

In the left hand condition, the distribution of turn decisions was 73.2% turning left and 26.8% turning right for the individual count data and 66.7% left and 33.3% right for the group-factored data. Again, these results clearly show a dramatic change in the turn-based decision that people made. The shift towards left turn decisions from

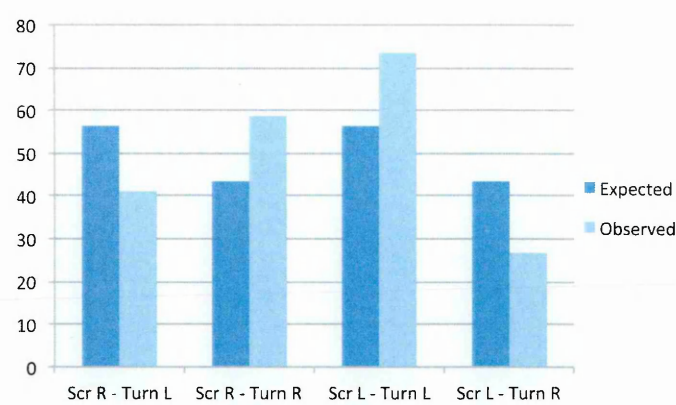
base data was higher than 18% for the individual count data and higher than 11% for the group factored data.

Graph 1. shows the percentage of left and right turn decisions in the two experimental conditions compared with base model data.



Graph 1. Showing the percentage of left and right turn decisions in different test conditions

Graph 2. shows the 'expected' percentage of turn decisions, recorded when no display was present in the corridor, against the results of the two experimental conditions.



Graph 2. 'expected' turn decision data recorded when no display was present.

Following the tests about the general significance of the measured data and the influence of the ambient display, a logistic regression analysis was conducted ('modeling of binomial proportions'). For this test a value denoting the position of the ambient display was introduced (direction of influence): '-1' when the ambient display is at the opposite side than the one testing, '0' when there is no display and '1' when the display is on the same side, as well as a value denoting the presence of an ambient display regardless of position (encoded as '0' for not present and '1' for present in one of the walls). The 'direction of influence' matches the direction of the significant change in movement as measured in the experiment, with a p-value (t pr.) less than 0.001.

The result of this analysis further confirms the hypothesis that the ambient display produces a significant change in the direction of movement towards the side at which the display is located. Additionally, combining the 'direction of influence' and the 'presence' variables evinces that the resulted distortion is not based on the side of

the corridor, where the ambient display is located, and thus for both 'right' and 'left' cases the change was equally significant.

5.4.4 Conclusion

Experiment 1 hypothesis:

The location of a digital display, which augments physical space by introducing augmented depth information, will influence how people move through a T-shaped corridor.

Building upon the findings of the pilot study, Experiment 1 was designed to provide a measurable behavioural outcome in a controlled experimental space. By doing so, the experiment was able to overcome some of the weakness of the pilot study findings due to its opportunistic nature, and clearly demonstrate the potential for behavioural change caused by the introduction of augmented visual depth information.

The results of the experiment showed clear support for the hypothesis. The statistical analysis conducted on the results showed that there were highly significant differences in the frequency of participants' right and left turn decisions in the two conditions, and compared with the base data, recorded when no display was present. These results were highly significant when comparing both individual count data, and also when group effects had been factored out of the data.

The direction of this shift in turn-based decisions showed that participants were more

likely to follow the path where augmented visual depth had been introduced. Base model and display testing examined the influence of the presence of the display unit, and digital images providing no visual-depth cues and found minimal influence, therefore, it can be concluded that it was the visual depth information provided by the display which caused people's behaviour to change.

This is a key finding with implications both for theory and practice and is discussed further in Chapter 6.

5.5 Experiment 2

5.5.1 Hypothesis

A display placed centrally in a T-shaped corridor, providing a skewed (either left or right) perspective projection of the space beyond the wall, will influence how people move through the corridor.

Manipulating the perspective, or skew, of a digital image which is acting as a 'window' to the space beyond a wall lengthens site lines towards the manipulated vanishing point, influences people's perception of space, and as a consequence, their behaviour.

5.5.2 Procedure

The display was mounted in the central position in all three of the experimental conditions. During the experiment the screen displayed a video feed of the target area beyond the corridor's wall. Three conditions were tested as follows:

1. Virtual window display – the display emulated a window by showing participants in the corridor a view of the target area that they would be able to see if the virtual display was replaced with a window. No skew was applied during this condition and the vanishing point of the image was centred.

2. Right-skewed window display – a video stream of the target area was shown in which the vanishing point had been manipulated to 45 degrees right of centre. This created a simulation of a window being viewed from the left.

3. Left-skewed window display - a video stream of the target area was shown in which the vanishing point had been manipulated to 45 degrees left of centre. This created a simulation of a window being viewed from the right.

Diagrams detailing the experimental set up in the three conditions are shown in figures 32 to 34 and figure 35 is a computer generation recreation of the visual experience of the participants during the experiment (right condition).

Study 2: Centered Perspective/Vanishing Point

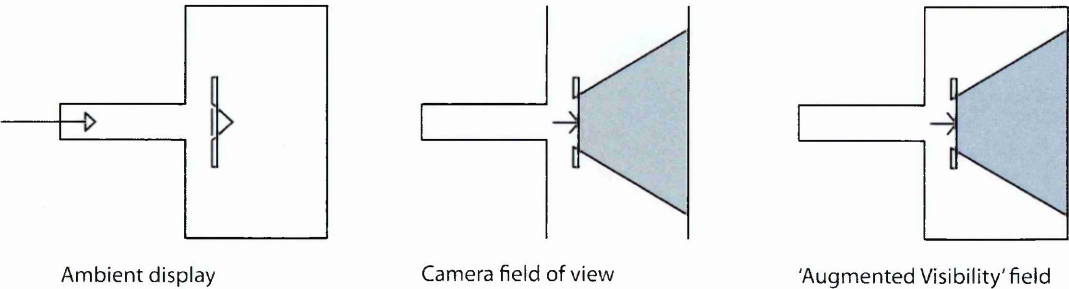


Figure 32. Experimental set up for the 'virtual window display' condition.

Study 2: 'Right-hand' Skewed Perspective / Vanishing Point on the right

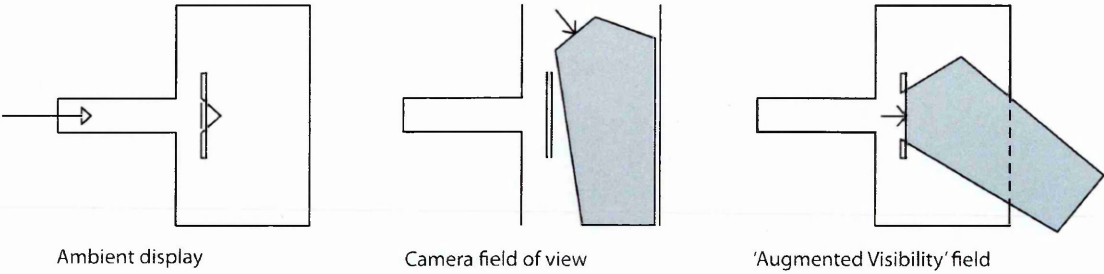


Figure 33. Experimental set up for 'Right skewed window display' condition.

Study 2: 'Left-hand' Skewed Perspective / Vanishing Point on the Left

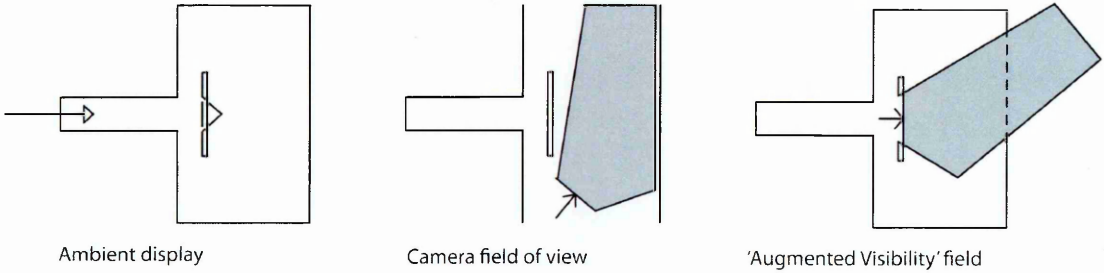


Figure 34. Experimental set up for the 'left-skewed window display' condition.

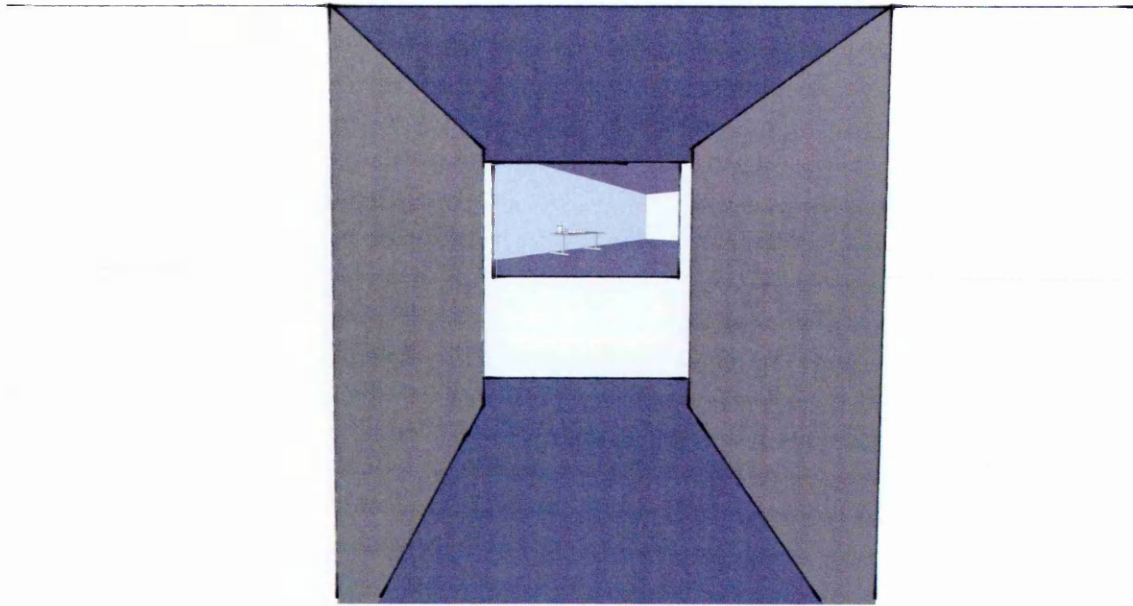


Figure 35 Computer generation recreation of the visual experience of the participants during the experiment (right condition)

5.5.3 Results

Full results for all conditions of Experiment 2 are shown in Table 11.

	Augmentation	Left turn (count)	Right turn (count)	Left turn (%)	Right turn (%)
Individual count data	Central	49	40	55.06	44.94
	Right	26	44	37.14	62.86
	Left	66	35	65.35	34.56
Group- factored data	Central	44	38	53.66	46.34
	Right	38	40	38.46	61.54
	Left	61	32	65.59	34.41

Table 11. Results of Experiment 2.

The results from the three unmatched groups of the three conditions were subjected to Chi-square analysis, Tables 12 and 13 provide the data which was subjected to the analysis and the test results are presented below. Table 12 shows the individual count data whilst Table 13 shows the group-factored data.

		Vanishing point of digital display			Total turn count
		Centre	Left	Right	
Left turn	Count	49	66	26	141
	Percentage	55.06	65.35	37.14	
Right turn	Count	40	35	44	119
	Percentage	44.94	34.65	62.86	
Total turn count		89	101	70	260

Table 12. Individual count data subjected to Chi-square analysis.

A Chi-square test on the data in Table 8 showed that there was a significant difference in the frequency of turn decisions in the conditions, X^2 (2, N = 260) = 13.29, $p = .001$.

		Vanishing point of digital display			Total turn count
		Centre	Left	Right	
Left turn	Count	44	61	25	130
	Percentage	53.66	65.59	38.46	
Right turn	Count	38	32	40	110
	Percentage	46.34	34.41	61.54	
Total turn count		82	93	65	240

Table 13. Group-factored data subjected to Chi-square analysis.

A Chi-square test on the data in Table 9 showed that there was a significant difference in the frequency of turn decisions in the conditions, $\chi^2 (2, N = 240) = 11.36, p = .003$.

In order to provide a comparison between the results of Experiment 2 and the base model data, recorded when no display was present, Tables 14 and 15 show individual count, and group-factored data, with base model data. Chi-square test results, conducted on the data shown in the tables are presented below.

		Vanishing point of digital display			Total turn count
		None – base data	Left	Right	
Left turn	Count	120	66	26	212
	Percentage	55.05	65.35	37.14	
Right turn	Count	98	35	44	177
	Percentage	44.95	34.65	62.86	
Total turn count		218	101	70	389

Table 14. Results of the Chi-square test conducted on individual count data from Experiment 2 and base model data.

A Chi-square test on the data in Table 10 showed that there was a significant difference in the frequency of turn decisions in the conditions, $\chi^2 (2, N = 389) = 13.3, p = .001$.

	Vanishing point of digital display	Total turn
--	------------------------------------	------------

		None – base data	Left	Right	count
Left turn	Count	101	61	25	187
	Percentage	54.89	65.59	38.46	
Right turn	Count	83	32	40	155
	Percentage	45.11	34.41	61.54	
Total turn count		184	93	65	342

Table 15. Results of the Chi-square test conducted on group-factored data from Experiment 2 and base model data

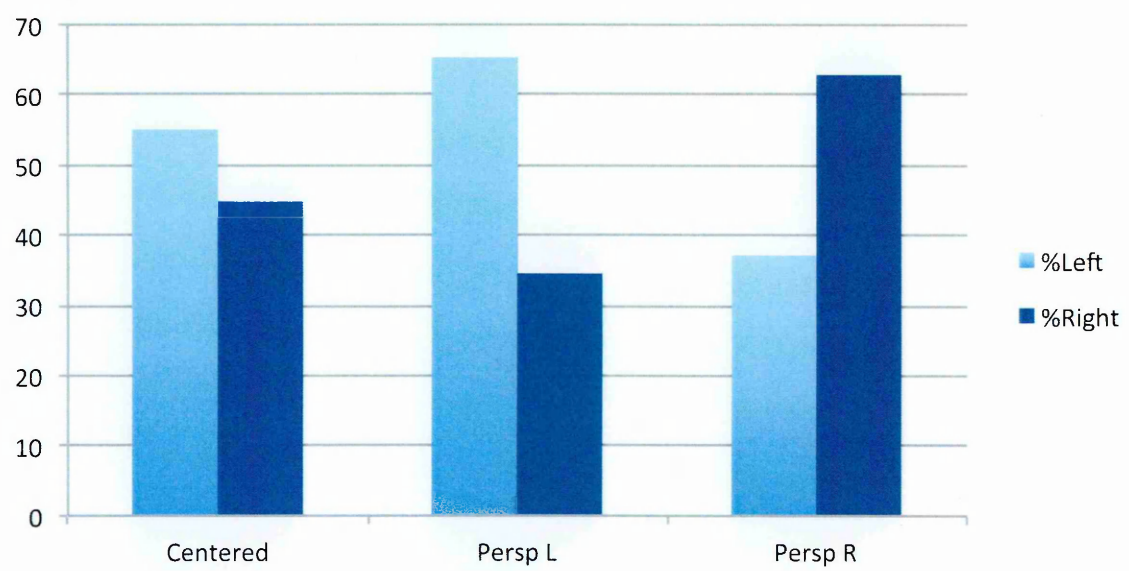
A Chi-square test on the data in Table 11 showed that there was a significant difference in the frequency of turn decisions in the conditions, $\chi^2 (2, N = 342) = 11.4$, $p = .003$.

The significance of the Chi-square test results can be observed in the percentages of turn-based decisions recorded during the different conditions. In the phase where the display perspective was centred the distribution was 55.1% turning left and 44.9% turning right for the individual count data and 53.7% left and 46.3% right for the group-factored data. Compared with the base data the results show minimal difference, suggesting that the presence of a centred perspective image had no impact on people's turn based-decision.

In the test condition where the display showed a right-skewed perspective image the distribution was 37.1% turning left and 62.9% turning right for the individual count data and 38.5% left and 61.5% right the group-factored data. These results showed a significant difference in the turn-based decision participants made. The shift towards right turn decisions from the base data was higher than 17% in the individual count data and higher than 16% in the group-factored data.

Finally, in the phase where the display produced an off-centred projection with a skewed perspective to the left, the distribution was 65.3% turning left and 34.6% turning right for the individual count data and 65.6% left and 34.4% right for the group-factored data. These results showed a significant difference in the turn-based decision participants made. The shift towards left turn decisions from base was more than 10% in both the group-factored and individual count data.

Graph 2 shows the percentage of left and right turn decisions in the three conditions.



Graph 2. Showing the percentage of left and right hand turn decisions in the three conditions.

Following the tests about the general significance of the measured data and the influence of the skewed projections, a logistic regression analysis was conducted ('modelling of binomial proportions'). For this test a value denoting the direction of the skewed projection of the ambient display was introduced (direction of influence): '-1' when the perspective's vanishing point is at the opposite side than the one

testing, '0' when there is centred and '1' when the vanishing point is on the same side, as well as a value denoting the presence of an ambient display regardless of projection (encoded as '0' for not present and '1' for present). The 'direction of influence' matches the direction of the significant change in movement as measured in the experiment, with a p-value (t pr.) less than 0.001.

This analysis further confirms the hypothesis that when the display shows a skewed image, a significant change in turn based decisions, towards the skewed vanishing point, is observed. Additionally, combining the 'direction of influence' and the 'presence' variables shows that the resulted distortion is not based on the location of the vanishing point (skewed perspective towards right or left), and thus for both 'right' and 'left' cases the change was equally significant.

5.5.4 Conclusion

Experiment 2 hypothesis:

A display placed in centrally in a T-shaped corridor, providing a skewed (either left or right) perspective projection of the space beyond the wall, will influence how people move through the corridor.

Building upon the previous research findings which showed that behavioural change was achievable though the introduction of 'digital windows' extending the visual-depth of an architectural space, Experiment 2 investigated whether manipulating the visual-depth information that participants were exposed to impacted upon their

behaviour. That is, whether 'false' visual-depth information can be used to create predictable movement patterns through the T-shaped corridor.

The experiment tested this through introducing a skew in the vanishing point of a digital display containing depth cues and compared people's behaviour in two conditions, left or right-skew, with a condition in which there was no manipulation of the visual-depth information provided by the display. Statistical analysis of the results showed that there was a highly significant difference in the behaviour of people in the different conditions, suggesting that the manipulation of the digital image did impact upon people's behaviour. This significance was found in tests conducted on both the individual count data and group factored data.

The results of the experiment showed that in the conditions where the skew was applied to the digital image, people were more likely to make a turn-based decision in the same direction of the skew. Therefore, the experiment shows that providing false depth cues through the use of digital displays, can successfully manipulate people's perception of depth, and this can impact on people's behaviour within architectural space. This finding has implications for theory and practice which are discussed further in Chapter 6.

CHAPTER 6 - CONCLUSIONS AND DISCUSSION

6.1 Development of the
hypotheses

6.2 Verification of the
hypotheses

6.3 Contributions

6.4 Further work

Chapter 6 - Conclusions and discussion

6.1 Development of the hypotheses

The chapter reviews the objectives of the research presented by the thesis and how these were met. The results of the research are reviewed in light of their implications for theory and practice and the potential for future research is discussed.

The overarching objective of the research presented in this thesis was to investigate the effect of augmenting the boundaries of physical architectural space by introducing digital displays providing visual depth cues.

Chapters 1 to 3 of the thesis introduce the research agenda by identifying a gap in current theories and techniques of space analysis, the importance of research to address this and the development of the methodological approach adopted for the research.

In more detail, the literature review provided by Chapter 2 shows how the research hypotheses were developed by reviewing two main fields of research. The first of these sections reviews visual perception and space cognition literature. Within this section existing theories of spatial and visibility analysis are reviewed, showing how

current theory understands the relationship between physical space, visual perception, and human behaviour.

The second section of the literature review examines ambient technology research, reviewing the current theory concerning the relationships between human perception, physical space and digital information (virtual space). This section focuses on ambient displays as an integral part of current and future architectural design and reviews research into human-computer interaction in order to understand the way in which ambient technology has become an integral part of people's everyday lives.

The key finding of the literature review was that theories of space analysis are able to account for physical architectural spaces and act as a useful tool under these conditions, however, they have not been developed to account for innovative recent developments in architectural design, which has seen the integration of ambient displays in everyday architectural space. Under these conditions it is possible for space analysis techniques to fail, because they do not account for the potential impact of the digital displays.

The aim of the research presented in this thesis, driven by the findings of the literature review, is that a digital display introducing visual-depth cues into static architectural space can operate as an opening or virtual window which can extend perceived architectural space and this shift in perceived space can influence people's behaviour within architectural space.

The overarching hypothesis guiding the research was as follows:

Ambient displays can be introduced into physical architectural settings to augment the perceived visual depth of a space by virtually linking and extending physical space towards another real or virtual space. This augments the topological and visual relations of a space which influences how people use and move within such settings.

From the overarching hypothesis more specific hypotheses were derived:

Digitally augmenting the perceived physical depth of a wall in a simple architectural setting will change people's use of the space.

The location of a digital display, which augments physical space by introducing augmented depth information, will influence how people move through a T shaped corridor.

A display placed in centrally in a T-shaped corridor, providing a skewed (either left or right) perspective projection of the space beyond the wall, will influence how people move through the corridor.

6.2 Verification of the hypotheses

Chapters 3, 4 and 5 detail the development of the experimental schema, the pilot, and the main studies respectively, describing the experimental design and procedure, the results and the conclusions that can be drawn from the data.

The results of the pilot study provided initial evidence to suggest that perception of spatial boundaries could be influenced by the introduction of digital visual-depth cues and confidence that the techniques employed were appropriate for the development of further experiments to examine the effect.

Specifically, the introduction of augmented visual-depth cues through the use of a digitally augmented wall, resulted in an increased use of space near this wall. This tendency increased when the augmented visual-depth was increased. The finding suggests that people perceived their physical space as increased when the digital depth of the wall was increased and used this 'digital' space as a result – so whilst they may have been standing close to a wall, they no longer perceived it as a flat wall, but continuing space.

The two main experiments developed the testing of the hypothesis by introducing a measurable outcome in participants' behaviour in controlled experimental conditions. The first experiment investigated the effect of positioning a digital display providing visual depth cues in a T-junction corridor requiring a turn-based decision by participants proceeding through the space. The results of this experiment showed that the location of an ambient display providing augmented depth information had

an impact on participants' turn-based decisions in the experimental space. An examination of the results showed that participants were more likely to turn towards the side of the corridor upon which the display was placed. In order to account for any effect of the presence of the display unit, and of images which provided no visual-depth cues, display tests were conducted prior to the commencement of Experiment 1. These showed that the display unit and images containing no depth-cues had minimal effect on turn decisions in the corridor, therefore, the change in behaviour shown in Experiment 1 was attributable to the visual-depth introduced by the image.

Building upon the findings of Experiment 1, the second experiment investigated whether manipulating the visual-depth information by providing 'false' visual-depth information, could cause predictable behavioural change in people's movement patterns through the T-shaped corridor. This was achieved by skewing the vanishing point of an image shown to participants moving through the corridor.

Statistical analysis conducted on the results of the experiment showed that there was a highly significant difference in the behaviour of people in the different conditions, suggesting that the manipulation of the digital image did impact upon people's behaviour. An examination of the results showed that people were more likely to make a turn-based decision in the same direction of the skew.

It is important to acknowledge that because of the use of a live feed from a camera, it was not possible to reproduce in the display a change in the perspective one would experience if the display was a window into another space. The live feed meant that

the perspective was static. Although the camera was carefully placed in order to have a very wide viewing angle and thus minimize the rate of change of perspective, future work would be useful to examine the effects of non-static perceptual illusions and how they may influence the distribution of people's movement.

6.3 Contributions

The research presented by the thesis makes a significant contribution the understanding of the behavioural impact of introducing augmented visual depth into static architectural environments.

The thesis identifies a gap in our knowledge and understanding of hybrid architectural space and human movement, and introduces the need for research to explore the impact of ambient displays integrated in architectural space.

The research identifies how current methodological approaches for the analysis of space are unable to account for hybrid architectural spaces and therefore need development in order to act as useful predictive tools in these environments.

The research demonstrates empirically that the introduction of digital depth has an impact on human behaviour in architectural space.

The detailed experimental findings include:

- If an ambient display projects a neutral two-dimensional image there is no impact on the way in which humans move and use the space in which it is presented. Within the context of the series of experiments, it is possible to suggest that this is because the display does not augment the visible depth of the space.
- When acting as a 'virtual window' through a wall, a visual display which extends the perceived depth of a space has the capacity to influence route selection through architectural settings.
- By skewing the vanishing point in digital displays and therefore extending the line of sight towards the vanishing point, people's route selection can be influenced. People are more likely to select a route which matches the skew of the projected image.

The research impacts upon architectural space design featuring ambient displays, as well as navigation in space. In the fast-growing field of digital augmentation in architecture, understanding and acknowledging people's movement, proximity and navigation in space can give new ways of managing and directing movement towards desired places or interfaces. Examples within this area include subliminal nudges for accessibility of remote or 'hidden' spaces as well as alternative and more efficient methods to assist way-finding. In addition, ambient information systems can be made and positioned in a way able to enhance interactivity and social engagement.

The research also has implications for the content and interface design of ambient media. In the field of human-computer interaction the design of the interface is of crucial importance for the effectiveness of the ambient displays. It is clear that people react to the virtual depth of the ambient interface, as indicated by the change in movement within the experiments, therefore, this needs to be taken into consideration during the design process.

By understanding the effects of ambient displays on people's movement through architectural space new possibilities for further research are made available.

By acknowledging the impact of ambient technology on people's behaviour, architects would be able to experiment with the use of different ambient media while being aware of their design proposals. Moreover, in the field of computer science, bringing together digital information and architectural space could facilitate new ways of weaving ambient technology into the fabric of everyday life.

From a theoretical perspective, the findings of this thesis contribute to the debates around how visual perception influences people's movement in architectural space. While human movement might tend to occur along the longest lines of sight and towards larger visible spaces, as Hillier and colleagues suggest (Hillier et al, 1993), the experiments in this thesis expose the complexities that arise in predicting human movement, when real and virtual spaces are blended together. Real and virtual spaces seem to have different affordances so in hybrid spaces the link between morphology and visual-based navigation needs to be further explored.

6.4 Further work

The research presented by the thesis demonstrates that it is possible to introduce virtual- depth in static architectural settings through the use of ambient displays which extend physical space into virtual space creating a hybrid system with new spatial configurations that established theories of space analysis cannot account for.

Therefore, the existing theories of space analysis need to be developed to account for the dynamic augmented depth introduced by digital displays in order to be successful predictive tools of people's behaviour within hybrid architectural spaces. Space needs to be considered as a dual system of physical and virtual space to be able to account for changes in depth perception caused by the introduction of virtual depth which has, as demonstrated, a real impact on people's behaviour in space.

As discussed in the literature review, further work is needed in order to superimpose virtual space onto real space and develop a way to analyse hybrid spaces using spatial analysis methods. Preliminary work (Varoudis, 2012b) investigates the extension of the isovists to an augmented visibility model. The paper considers a simple isovist analysis that includes virtual 'hyperlinks' between dislocated elements of space. An attempt was made to incorporate the virtual space originally projected on the digital display in Experiments 1 and 2 onto the real space. Visibility graph analysis (Figure 36) shows there is a possibility to replicate the results of the experiments, however, it exposes the problem of overlap. Simply adding the virtual

space onto the real space layout results in having points in the analysis that represent two spaces, which cannot be analysed using traditional analysis techniques.

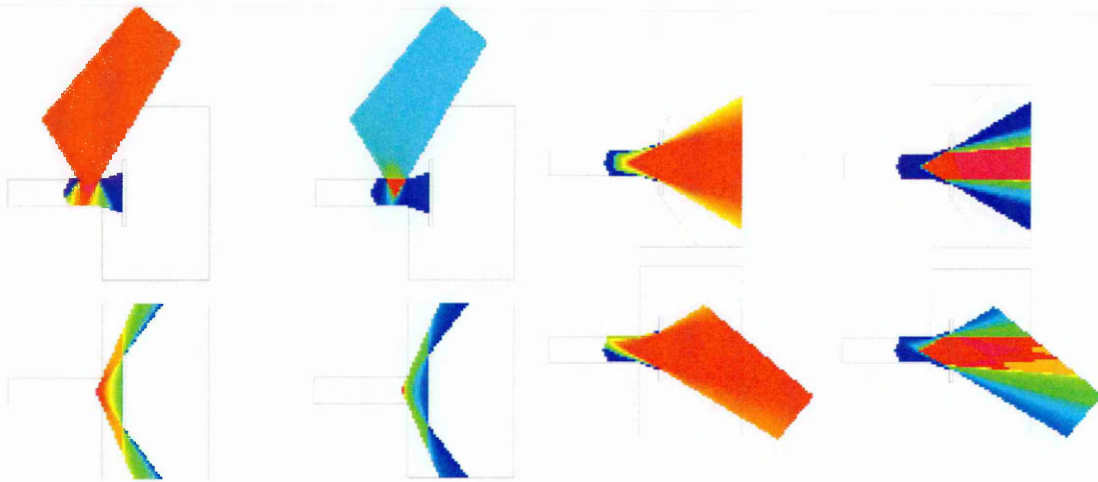


Figure 36 Novel VGA analysis that includes the augmented isovist boundary and exposes the overlap problem

This introduction of new transparencies, through the use of ambient projections that extend physical space into virtual worlds, creates a dual system with new spatial configurations resulting from the introduction of altered virtual depth which can account for the change in behaviour in digitally altered settings observed in the research presented in the thesis. Further research is needed to produce more insights that might help use augmented visibility analysis in more complex environments. The belief is that the impact in human navigation and perception of space will be more intense in hybrid environments where the augmented virtual depth makes the visibility and angular relations fluid as we increase the complexity.

This makes the idea of augmented visibility analyses a very important asset with applications in navigation and analysis of hybrid spaces and spaces where visibility does not always match accessibility. In environments like that, subliminal nudging for accessibility of remote or 'hidden' spaces as well as alternative and more efficient methods to assisting way-finding are crucial.

Finally, to address the computational problem of analysing spaces that include 'augmented visibilities' and areas that include 'inaccessible but visible' locations, it is suggested that a 'mixed-directionality graph structure' could be useful (Varoudis, 2014, awaiting publication). In 'Augmented Visibility Graph Analysis: Mixed-directionality graph structure for analysing architectural space'. (Varoudis, 2014, awaiting publication), a proposition is made that a mixed use of directed and undirected graph edges can be used in order to analyse such settings, presenting the definition of 'Augmented Visibility Graph Analysis' or 'AVGA' and a series of graph measures.

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Publications Deriving From This Research

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Ambient Displays: Influencing Movement Patterns

Abstract. Ambient displays are gradually augmenting the principal static elements of architecture, such as walls, transforming space into a dynamic and ever-changing environment. Does the addition of such digital elements influence people's perception and understanding of space around them? If so, do ambient displays lead to behavioral changes like people's movement in such environments? In this particular study, a series of experiments were conducted to investigate public interior spaces with embedded ambient displays. The findings are then presented showing how the presence of an ambient display through its visual depth affects and changes movement patterns. This study discusses the ability of an ambient display to refine navigation paths and suggests that its visual depth can enhance its effectiveness.

Keywords: Ambient displays, human navigation, built environment, visual perception.

1 Introduction

Digital technologies have now become a medium for transforming the principle elements of architecture into dynamic components that affect people's perception and understanding of the space around them. Ambient displays, in most cases, can simply augment walls and thus have an advantage of not changing the physical morphology of space. Through light and sound, they make use of the entire physical environment as an interface and source to digital information [1]. This interface can be considered as a virtual opening, in a form of a digital window that extends the architectural space and widens the vision of users in a given space. Like a window that connects two physical spaces and transfers information between them, an ambient display can be seen as a link between physical and virtual worlds, where the virtual world can be for example the projection of another physical world or a computer generated space.

The introduction of a virtual space into the physical environment redefines the spatial properties of this environment. For instance, an ambient display can be used to transform a static wall to a more transparent and fluid element that dissolves the boundaries between

virtual and physical space. During 'out of bounds' interactive installation, Chris O' Shea [2] effectively challenged the relation between physical and virtual space. By projecting previously captured spaces onto the wall, he enabled people to 'see' through the physical boundaries of space. As he stated, this interaction allowed people to enter the 'prohibited' areas of the museum while encouraging their childlike curiosity [2]. But how can ambient displays affect people's movement in space? The ability of ambient displays to project views of one space from another and create hybrid information space might alter our perception of space. If so, can the use of hybrid space create behavioral changes related to people's navigation in space?

The aim of this research was to analyze how digital information when introduced through ambient displays affects people's movement in the interior of public architectural spaces. The research's interest is in how the addition of an ambient display at a given space can alter people's navigation in it. In order to answer this, a series of experiments were designed to explore the effects of ambient displays on people's movement inside public spaces.

2 Background

Research from two fields is relevant to the work. First, this research examines work investigating the use of ambient technology in architectural spaces. Second, there is a brief outline of research studying perception and movement in architectural spaces, where ambient displays are not considered as elements that augment vision.

2.1 Ambient Displays: Transforming Architectural Spaces

The paradigm of ubiquitous computing represents the technological tendency of embedding

information processing into everyday objects and activities. Drawing on Weiser's proposal of 'ubiquitous computing' [3], Ishii and Ulmer [4] envisioned the transformation of architectural surfaces into active interfaces between physical and virtual worlds. One of the first attempts to place an ambient display inside architectural space was initiated by Ishii et al. [5]. They designed the ambientROOM, a room equipped with ambient media (ambient light, shadow, sound, airflow, water flow). AmbientROOM provided the inhabitation of a room with a subtle awareness of human activity around people. The environment created by the ambientROOM was designed to enhance the sense of community through shared awareness concluding in a more pleasant space.

Currently, ambient displays have received considerable attention by architects who try to construct buildings with embedded digital technologies. For example, the Porsche Museum by Delugan Meissl [6] (see Figure 1) and the BMW Museum in Munich, Germany that was designed in 2007 by ART+COM [7] include large ambient displays that have augmented the interior surfaces of walls. In addition to this, when they designed Digital Pavilion in 2006, Kas Oosterhuis and Ilona Lénárd [8] transformed concrete interior walls into interfaces able to display readable information or create atmospheric lighting effects. Taking the idea of placing ambient displays instead of walls further, Ataman et al. [9] proposed the use of large display 'materials' as construction surfaces in architectural design. They envisioned movement through space in the future to be more dynamic, incorporating different levels of transparency and space that could be described by the fluidity of the walls that surround people.

As indicated by previous studies [10, 11], the presence of an ambient display in architectural space can ensure more pleasant environments; while at the same time can be informative



Fig. 1. Porsche Museum, Stuttgart, Germany

and socially engaging. Moreover, because of being blended with physical space, ambient displays are unobtrusive and do not distract the users that are not interested in the displayed content. For example, Mathew and Taylor [10] with their project AuralScapes try, with the use of sound and sky projections, to create a virtual connection from the outside to the inside, where information is abstracted and delivered at the periphery of human attention. By developing this link, they create a pleasant indoor environment and partially dissolved the static notion of the surrounding walls.

In fact, the use of digital technologies in architecture goes beyond the simple modification and transformation of space into a pleasant and informative environment, influencing people's behavior in it. With his work Röcker et al. [12] states that ambient display installations that promote awareness and presence produce positive effects and behavioral changes on office teams.

It has been observed that changes to the digital environment have led to behavioral changes such as the movement of people through that space. Indeed, Fatah gen. Schieck et al. [13] in an attempt to analyze the influence of an interactive floor installation in people's social engagement in urban environments, reports that she recorded unexpected and diverse changes in movement patterns around the installation. But what are the changes in movement patterns resulting from the presence of ambient technology?

For architects wanting to incorporate ambient interfaces it is essential to acknowledge the effects of their design proposals on people's navigation in space. With analysis and visualization of these effects, ambient display components will be incorporated in designs efficiently and activate or transform existing spaces. Relevant studies [6, 14, 15, 16] on ambient technology place the center of attention on human-computer interaction without considering the visual and spatial perception that link people and technology.

2.2 Perception and Movement in Architectural Spaces

It is generally accepted in architecture that the structure and configuration of space affect people's navigation and movement. Gibson's research, which was primarily developed for visual perception, suggests that our senses provide us with direct awareness of the external world and its properties [17]. People perceive space through their senses and act accordingly, thus there is a tight relation between perception and movement.

Based on this theory, architect and virtual reality pioneer Benedikt [18] proposed that space is perceived as a collection of visible surfaces that are not obstructed by physical boundaries and he defined 'isovists' to describe the area in the environment that is directly visible from

a location within space. A single isovist is the area of space directly visible from a given location in space, together with the location of that point. For example, in a convex space or a rectangular space with partitions the isovist area of a given point may not include the full area of that space and some parts of the space will not be directly visible from other points in space (see Figure 2).

Another urban and architectural theory that is relevant to this study is 'Space Syntax'. Hillier and Hanson proposed 'Space Syntax' to describe and analyze the character of a space and its effects on human behavior [19]. 'Space Syntax' research shows that the majority of human movement occurs along the longest lines of sight, and that the more open visible space we have in front of us the more we tend to move towards that direction [20].

However, the complexity of the spatial elements that are taken into consideration is limited. 'Space Syntax' sees space as a set of solid walls and empty openings and does not examine transparent elements. In addition to the lack of consideration of transparent materials, there is also a lack in understanding the effects of ambient technologies and 'digital' transparencies. Both physical and 'digital' transparencies may have important effects on people's perception of space and movement within it as they both extend and sometimes distort the depth of field.

Existing spatial analysis theories do not take into consideration complex architectural components such as ambient displays. Despite the fact that there are some studies that deal with pervasive systems in urban environments, they focus on social behavior and do not consider the influence of ambient displays on human movement [13, 21]. Additionally, such research is limited in considering ambient technology as a layer that is placed over existing urban infrastructures or simply replaces building facades. As we move into a world where a fusion of virtual and physical is going to be prevalent [22], studying and analyzing people's behavior in relation to the use of embedded ambient displays can offer important knowledge.

3 Aims and Objectives

The study starts with the assumption that the topological and visual relations between physical spaces are two important factors that determine the distribution of people's movement in space [23].

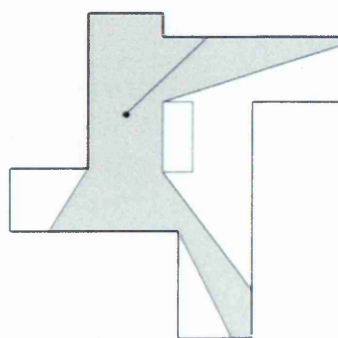


Fig. 2. Isovist field: grey color indicates the visible area from point

This research intends to analyze the changes in movement patterns when ambient displays are used as a virtual extension of the visual boundaries inside public architectural spaces. The hypothesis of this study is that placing ambient displays that virtually link and extend one physical space towards another that is near but not directly accessible will influence the topological and visual relations between spaces and as a result will affect the distribution of people's movement (see Figure 3).

Analyzing the effects of ambient displays on movement patterns when are blended in architectural spaces and induce virtual augmentation would provide a better understanding of the relation among humans, space and ambient displays. In contrast to current stable physical spaces, the introduction of new responsive and ever-changing materials will impose new fully adaptive architecture. Therefore, extending current knowledge and theories to involve digital transparencies as a crucial element of spatial configurations is inevitable.

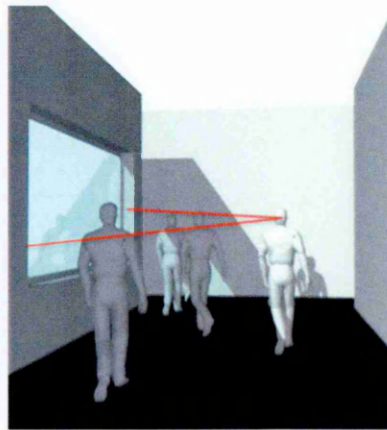


Fig. 3. Ambient display as digital transparency

4 Methodology

To achieve the aims of this research, a series of experiments were developed in order to observe and analyze people's movement in different spaces depending on the presence of ambient displays (see Figure 4). The experiments are focused on the use of ambient displays in the interior of public architectural spaces by placing them near a place of common interest. The main reason behind the use of public architectural spaces is that public spaces offer great opportunities for experimenting with ambient technology and the analysis of movement. From a methodological perspective, such places allow observing the movement behavior of a significant amount of people providing a larger sample for experimentation and analysis.

A fundamental form of space, in which it is simple to examine the flow and direction of people between discrete routes, is corridor-like settings. Based in this setting, two distinguished routes are needed, from which the users can choose in order to access the target space. 'Target space' is considered as a space with common interest for the participants of the experiment such as a coffee area or a common room that they can prepare and eat their lunch.

This type of experiment gives the opportunity to examine a single 'decision making' point providing clear and unbiased experimental conditions. It is essential that the routes need to be symmetrical in order not to influence the users' choice by producing different visual triggers. Moreover, having the 'T' shaped corridors as the setting, where people can go left or right, gives symmetrical visual characteristics. Therefore, the addition of an ambient display just before the corner as depicted in Figure 5 is expected to act as a visual trigger. The display's position near the corner will potentially introduce a digital opening in the visual field and will influence people's movement.



Fig. 4. Example of an experiment setting. Ambient display embedded in wall to the left.

Intuition and a simplistic interpretation of 'Space Syntax' suggest that the presence of an ambient display in a corridor should not influence the route decision-making choices of occupants going down this corridor. In the condition when both routes are equidistant from the objective, one might well expect a 50/50 left-right split of occupants. Alternatively, the hybrid space hypothesis suggests that a digital ambient display that functions like a virtual window will alter spatial morphology and so will result in an observable behavioral change



Fig. 5. Influencing direction of movement. Ambient display embedded in wall to the right.

in movement patterns (see Figure 5). To test this, a set of corridors as a 'T-shaped' arrangement was constructed with the upper part of the 'T' near the target space. As the 'target space', a room for coffee providence and preparation was used, since it is more attractive for daily visits for both staff and visitors. The research's interest is to examine how the addition of an ambient display would affect this distribution, a case that currently is not predictable by relevant theories like 'Space Syntax'.

Having set an outline of the experimental requirements, the design phase divided in three parts. The first part is focused on the ambient display and its content while the second part

on spatial setting. The third part is a combined effort for the effective placement of the ambient display in the particular space.

Deriving from the background research and the hypothesis, the display's main function was to act as a live video link providing a one-way video from the 'target space' and introducing an augmented opening that digitally expands vision. In addition, a series of 'null-tests' were introduced as part of the experiment using the ambient display with: no content, random static images and random animated content. The 'null-tests' were critical for establishing the content of the display as the only source of influence.

4.1 Experimental Set-Up

The space used was the Ambient Technology Lab at the Open University UK. It is a space of approximately 144 m² that is free of internal walls and can be configured in any arrangement easily with little limitations. For the construction of the corridor-like setting lightweight solid partitions were used covering the full height of the space and positioned in order to produce a symmetrical space. The remaining space at the end of the corridor-like setting was designed as a small cafeteria with sufficient space for people to stay and chat with each other reproducing a casual everyday atmosphere. Over the course of the experiment there was free coffee, tea and some sweets in this space available to everyone.

For the data gathering, a multi-camera set-up was used for synchronized recording of every corner of the lab. The cameras were positioned in the ceiling and configured to track multiple angles of the decision-point area as well as the full length of the corridor and the coffee area. Additionally, the cameras could also focus on the face along with the body of

each subject in order to recognize the line of sight, as each subject was moving towards and passing the decision point. For every day of the experiment eight video streams were recorded during the working hours.

The experiment ran over a period of several weeks where people that work in the university or visitors could use this setting for taking their morning or afternoon coffee. None of the participants were aware of the research's nature but were informed that they were taking part in an experiment and would be recorded. The experiment area was clearly marked to the effect that they are entering a video monitored zone and emails sent out to ask for participants. The emails explained that the purpose of the experiment will be revealed after its compilations and the whole process was ethically approved. While participants were asked to use a specific entrance and exit door in order to avoid passing through the corridor in both directions, it was felt that this did not bias participants' response of direction choice.

As discussed before, the measurements had to be compared with a 'base model' of this space with no ambient displays installed. On that account, the experiment started by collecting data about people's movement within the T-shape configuration with no ambient display present. After having sufficient data to serve as the basis of the experiment, the second phase started, in which a large display was carefully embedded into the right wall (see Figure 6) of the constructed corridor just before the corner (decision point). The display, a large anti-glare display with a 15 mm black casing, was linked with a high-definition professional camera and depicted the coffee area as seen from a particular 'perspective'. This 'perspective' view was used in order to emulate the actual perspective of the coffee area that an opening at this position would have revealed. Similarly, in the third

phase the display was placed symmetrically on the left side of the corridor, positioned in the same way and producing the same effect but streaming data of the coffee area as seen from

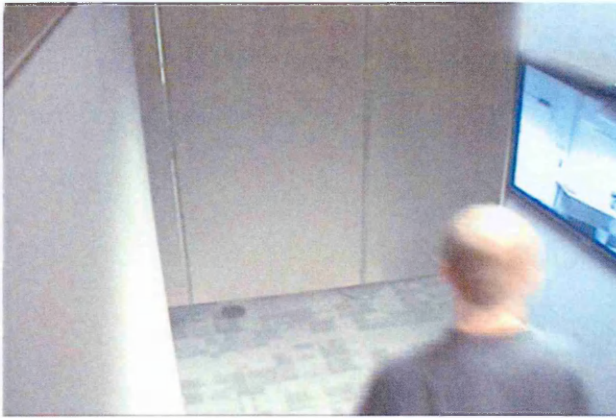


Fig. 6. Example of an experiment setting. Ambient display embedded in wall to the right.

the left side. Everything else in the experimental setting remained unchanged for the course of the experiment. At the end of the study all video streams were examined regarding the movement, choice of direction and the reactions of the people. All data were treated with confidentiality and not shared with anyone outside the limits of this research.

4.2 Initial Reactions – Video Observation

To capture people's initial reactions to the ambient display the recorded video, which was taken from cameras tracking people's movement while approaching the decision point, was observed. Upon approaching the display a small percentage of people were seen to momentarily stop and look at it for just a second and then turn towards the route of the screen. The majority of people only seemed to take a glimpse of the screen by turning their head slightly and then turn at the corner. Although the video revealed that most of the

individuals took their decision quickly, some individuals changed their initial decision and finally moved towards the side of the display. Overall, while the ambient display was something new to their environment less than 0.01% of people who took part in the experiment seemed unfamiliar to its presence. In total, more than 800 individuals took part in the experiment, which gives us a clear evaluation of the hypothesis. The number of participants doesn't include people passing multiple times but the observations are kept in order to later check their potential contribution on the overall hypothesis.

5 Results

To analyze the movement patterns in the experimental setting the number of individuals and groups walking through the corridor were counted in relation to their decision to follow the right or left direction in the particular setting. The data were categorized according to the experimental phase (without display, with the display on the left and with the display on the right) and whether it was individuals or groups. The analysis conducted by grouping the data into two categories in order to eliminate any signs of internal influence within the groups of people ('groups' have more than one person and all subjects follow the first person in the group): 1) for 'all groups and individuals' without taking into account if a person was alone or a part of the group and 2) 'only individuals' counting all 'individuals' and each of the 'groups' as one subject unaffected by the number of people in the group. These categories were analyzed using a chi-squared test and logistic regression analysis (modeling of binomial proportions).

In the first phase (no display), which took place over a period of four weeks, the findings revealed that combining groups and individuals, 55% of the people turned left in the specific setting and 45% turned right, while counting only the individuals the distribution was 54.8% left and 45.2% right (see Figure 7).

In the second phase where the display was on the right side and run over a period of three weeks, the distribution was 41.1% turning left and 58.9% turning right for the combined test subjects and 42.1% left and 57.9% right for only the individuals (see Figure 7). Those results

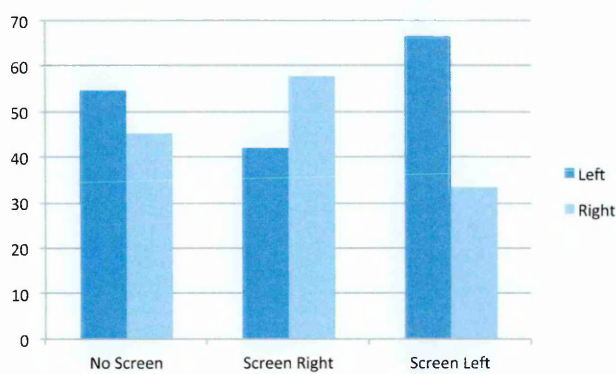


Fig. 7. Distribution (%) between routes.

showed a significant 'shift' in people's distribution along the two alternative directions. The shift towards the right side was 13.9% combining all test subjects together and 12.7% counting only the individuals.

Finally, in the third phase with the display positioned on the left side and run for three weeks, the distribution was 73.4% turning left and 26.6% turning right for the combined test subjects and 66.6% left and 33.4% right for only the individuals. Those results also showed a

significant 'shift' in people's distribution (see Figure 7). The shift towards the left side was 18.4% combining all test subjects together and 11.8% when counting only the individuals.

Furthermore, for validation of the significance of the results from the three unmatched groups a chi-square statistical test was used. The p-value of this test was 0.000047. Figure 8 depicts the calculated 'expected' percentages from the chi-square test against the observed percentages.

Following the tests about the general significance of the measured data and the influence of the ambient display, a logistic regression analysis was conducted ('modeling of binomial proportions'). For this test a value denoting the position of the ambient display was

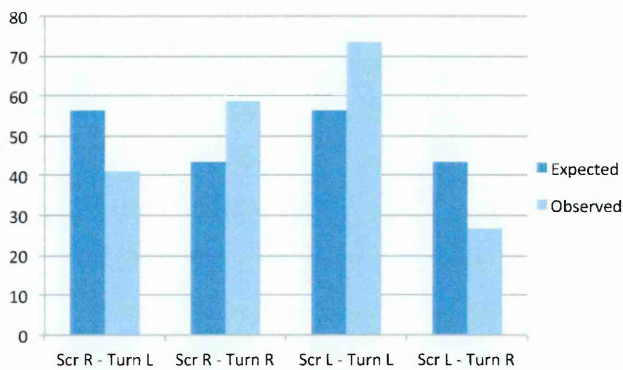


Fig. 8. Expected and observed (%) movement distribution.

introduced (direction of influence): '-1' when the ambient display is at the opposite side than the one testing, '0' when there is no display and '1' when the display is on the same side, as well as a value denoting the presence of an ambient display regardless of position (encoded as '0' for not present and '1' for present in one of the walls). The 'direction of

influence' matches the direction of the significant change in movement as measured in the experiment, with a p-value (t pr.) less than 0.001. The result of this analysis further confirms the hypothesis that the ambient display produces a significant change in the direction of movement towards the side at which the display is located. Additionally, combining the 'direction of influence' and the 'presence' variables evinces that the resulted distortion is not based on the side of the corridor, where the ambient display is located, and thus for both 'right' and 'left' cases the change was equally significant.

5.1 Null-Tests Results

The results presented until now showed that the presence of an ambient display influences how people move through the environment. However there was a need for extracting whether the ambient display itself (the device) or its content were responsible for that change. For that reason, using the same equipment and spatial setting a follow-up experiment was conducted positioning the display in the same places as the first experiments but without the video link. Instead of the video feed, several scenarios were tested: no image is used in order to test the ambient display as a device while static images, animated images and short video clips used to explore the effects of diverse content that could affect the users.

The results were treated in the same way as the first experiment and showed that the shift in direction between the phase without a display (base model) and each of the null-test phases is less than 3% in all cases and not statistically significant.

In detail, from more than 400 individuals who took part in the null-test experiments, the

majority of people continue to use the left route more (the same way as before the application of the ambient display), with the percentage varying from 57% to 53% in favor of the left route. More analytically, compared to the phase without an ambient display where the distribution was 55% left and 45% right, the distribution with the display on the left for the worst case null-test scenario (case with the largest shift) was, 57.8% left and 42.2% right; while with the display on the right, 53.2% left and 46.8% right. What is clearly visible from the results is that the ambient display blends in the environment and becomes an unobtrusive object that without the visual extension does not influence people's behavior and movement in space.

6 Conclusion

The results of this study reveal that, an ambient display that shows typical information has, as one might expect, no change on pedestrian route choice behavior. If the display shows a projection of nearby space, relevant to the pedestrian, then the presence of the augmented visual depth and more particularly the position of the ambient display influences route choice behavior. This has a number of ramifications in terms of both the design of ambient displays in architectural settings and the use of augmented/hybrid spaces in research conditions.

Combining the findings from the experiment and the observation from the recorded video it is concluded that there is a significant change in the distribution of people and their movement patterns when an existing architectural space is augmented by the presence of an ambient display projecting a virtual link between two physically disconnected spaces

(where the one can be also a virtual representation of a space). It is also clear from the results that the position of the display in the symmetrical routes has no different effects regarding the distortion of movement. In addition to this, the results of the 'null-tests' addressed that when the ambient display is not producing an augmentation of the visual field or the visual depth, it does not influence people's movement in space.

This study also demonstrates that the position of the ambient display as a visual link to a near but physically disconnected location has the effect of increasing awareness about this space giving a subliminal direction towards the side where the screen is situated. In some cases the ambient display unconsciously nudged people to pass through the corridor setting and go to the coffee area. As the video revealed, most of the users took decisions quickly. However, there were cases of individuals changing their initial decision and adapting their route towards the side of the screen. It is speculated that raising awareness of this decision may have increased the likelihood that these individuals recalculated the new augmented layout of space against the old and moved accordingly.

Accepting that people's visual perception of space becomes influenced by the virtual augmentation and extension of space that ambient displays produce, this research can contribute in two main areas. One area deals with the architectural space design featuring ambient displays, as well as navigation in space. The second area is the content and interface design for ambient media. In the fast-growing field of digital augmentation in architecture, understanding and acknowledging people's movement, proximity and navigation in space can give new ways of managing and directing movement towards desired places or interfaces. Examples within this area include subliminal nudges for

accessibility of remote or 'hidden' spaces as well as alternative and more efficient methods to assist way-finding. In addition, ambient information systems can be made and positioned in a way able to enhance interactivity and social engagement.

In the field of human-computer interaction the design of the interface is of crucial meaning for the effectiveness of the ambient displays. As it is clear that people react to the virtual depth of the ambient interface, as indicated by the change in movement within the experiments, designing such interfaces needs a significant consideration of the results that they will induce. As this study shows, an ambient display that extends the visual depth acts as a subliminal element attracting people to approach it and also change their direction. This effect is clear when comparing the findings from the 'null-test' with the main experiment.

Further research is needed, however, to produce more generic insights that might help with ambient display usage in architectural space and more critically the interface design itself. For this reason, it is crucial to explore more areas of the visual augmentation of spatial boundaries with ambient displays. Currently, a research that explores how the directionality of the virtual perspective projection, which is produced by ambient displays, can influence people's direction of movement and proximity from the display is in its final stages. In essence, the intention is to produce attraction and movement by using skewed perspective projections on statically positioned ambient displays.

This research suggests that embedding ambient displays that extend the visual depth into space can engage people to adhere to certain kinds of desired movement patterns.

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Subtle interventions: How ambient displays influence route choice

in buildings.

Abstract. Ambient displays allow physical space to be transformed into a dynamic and ever-changing environment in which boundaries are dissolved. However, it is likely that the incorporation of such digital elements affects people's perception and understanding of space. In this particular study, a series of experiments were conducted to examine how a skewed perspective projection via an ambient display influences people's navigation in public spaces. The findings are then presented showing how the participants' responded to the presence of the skewed projection and the effects on the movement patterns. This study discusses the ability of an ambient display to influence navigation paths and suggests that a projection with skewed perspective can determine the creation of new movement patterns.

Keywords. Ambient displays; human navigation; built environment; visual perception; isovist.

Introduction

Space can no longer be seen as a simple composition of static elements. The introduction of ambient displays that simply augment walls causes the boundaries to unfold and reveal hybrid spaces. These interfaces can be considered as digital openings in a form of virtual windows that extend architectural space and widen the vision of users in a given space. Like a window that connects two physical spaces and transfers information between them, an ambient display can be seen as a link between physical and virtual worlds, where the virtual world can be for example the projection of another physical world or a computer generated space. Drawing on this approach, ambient displays can maintain a subtle but highly informative connection with humans and create dynamic and ever-changing environments.

When a virtual space is introduced into the physical environment, the spatial properties are redefined. For instance, an ambient display can transform a static wall to a more

transparent and fluid element that dissolves the boundaries between virtual and physical space. During 'out of bounds' interactive installation, Chris O' Shea [1] effectively challenged the relation between physical and virtual space. By projecting previously captured spaces onto the wall, he enabled people to 'see' through the physical boundaries of space. As he stated, this interaction allowed people to enter the 'prohibited' areas of the museum while encouraging their childlike curiosity [1]. But how can ambient displays affect people's movement in space? The ability of ambient displays to project views of one space from another and create hybrid information space might alter our perception of space. If so, can the use of hybrid space create behavioural changes related to people's navigation in space?

The aim of this research was to analyse how digital information projected with skewed perspective through ambient displays affects people's movement in the interior of public spaces. The research's interest is in how the manipulation of the projection angle of an ambient display at a given position can alter people's navigation. In order to answer this, a series of experiments were designed to explore the effects of ambient displays on people's movement inside public spaces.

Background

Research from two fields is relevant to the work. First, this research examines work investigating the use of ambient technology in architectural spaces. Second, there is a brief outline of research studying perception and movement in architectural spaces, where ambient displays are not considered as elements that augment vision.

Ambient Displays: Transforming Architectural Spaces

Ambient displays have received considerable attention by architects who try to construct buildings with embedded digital technologies. For example, the Porsche Museum by Delugan Meissl [2] (see Figure 1) and the BMW Museum in Munich, Germany by ART+COM [3] include large ambient displays that have augmented the interior surfaces of walls. In addition to this, when they designed Digital Pavilion, Kas Oosterhuis and Ilona Lénárd [4] transformed concrete interior walls into interfaces able to display readable information or create atmospheric lighting effects. Taking the idea of placing ambient displays instead of walls further, Ataman et al. (2006) proposed the use of large display 'materials' as construction surfaces in architectural design. They envisioned movement through space in the future to be more dynamic, incorporating different levels of transparency and space that could be described by the fluidity of the walls that surround people.

As indicated by previous studies (Wisneski et al, 1998; Mathew et al, 2008; Tomitsch et al, 2008), the presence of an ambient display in architectural space can ensure more pleasant environments; while at the same time can be informative and socially engaging. For



Figure 1
Porsche Museum, Stuttgart, Germany.

example, Mathew and Taylor (2008) with their project AuralScapes try, with the use of sound and sky projections, to create a virtual connection from the outside to the inside, where information is abstracted and delivered at the periphery of human attention. By developing this link, they create a pleasant indoor environment and partially dissolved the static notion of the surrounding walls.

In fact, the use of digital technologies in architecture goes beyond the simple modification and transformation of space into a pleasant and informative environment, influencing people's behaviour in it. With his work Röcker et al. (2004) states that ambient display installations that promote awareness and presence produce positive effects and behavioural changes on office teams.

It has been observed that changes to the digital environment have led to behavioural changes such as the movement of people through that space. Indeed, Fatah gen. Schieck et al. (2007) in an attempt to analyse the influence of an interactive floor installation in people's social engagement in urban environments, reports that she recorded unexpected and diverse changes in movement patterns around the installation. But what are the changes in movement patterns resulting from the presence of ambient technology?

For architects wanting to incorporate ambient interfaces it is essential to acknowledge the effects of their design proposals on people's navigation in space. With analysis and visualization of these effects, ambient display components will be incorporated in designs efficiently and activate or transform existing spaces. Relevant studies (Ishii and Ulmer, 1997; Ishii et al, 1998; Prante et al, 2003; Jafarinaimi et al, 2005) on ambient technology place the

centre of attention on human-computer interaction without considering the visual and spatial perception that link people and technology.

Perception and Movement in Architectural Spaces

It is generally accepted in architecture that the structure and configuration of space affect people's navigation and movement. Gibson's research, which was primarily developed for visual perception, suggests that our senses provide us with direct awareness of the external world and its properties (Gibson, 1979). People perceive space through their senses and act accordingly, thus there is a tight relation between perception and movement.

Based on this theory, architect and virtual reality pioneer Benedikt (1979) proposed that space is perceived as a collection of visible surfaces that are not obstructed by physical boundaries and he defined 'isovists' to describe the area in the environment that is directly visible from a location within space. A single isovist is the area of space directly visible from a given location in space, together with the location of that point. For example, in a convex space or a rectangular space with partitions the isovist area of a given point may not include the full area of that space and some parts of the space will not be directly visible from other points in space.

Another urban and architectural theory that is relevant to this study is 'Space Syntax'. Hillier and Hanson (1984) proposed 'Space Syntax' to describe and analyse the character of a space

and its effects on human behaviour. 'Space Syntax' research shows that the majority of human movement occurs along the longest lines of sight, and that the more open visible space we have in front of us the more we tend to move towards that direction (Hillier et al, 1993). However, the complexity of the spatial elements that are taken into consideration is limited. 'Space Syntax' sees space as a set of solid walls and empty openings and does not examine transparent elements. In addition to the lack of consideration of transparent materials, there is also a lack in understanding the effects of ambient technologies and 'digital' transparencies. Both physical and 'digital' transparencies extend and sometimes distort the depth of field or the perspective angle and thus may have important effects on people's perception of space and movement.

Existing spatial analysis theories do not take into consideration complex architectural components such as ambient displays. Despite the fact that there are some studies that deal with pervasive systems in urban environments, they focus on social behaviour and do not consider the influence of ambient displays on human movement (Fatah gen. Schieck et al, 2007; Fatah gen. Schieck et al, 2005). Additionally, such research is limited in considering ambient technology as a layer that is placed over existing urban infrastructures or simply replaces building facades. As we move into a world where a fusion of virtual and physical is going to be prevalent (Spiller, 2002), studying and analysing people's behaviour in relation to the use of embedded ambient displays can offer important knowledge.

Aims and Objectives

The study starts with the assumption that the topological and visual relations between physical spaces are two important factors that determine the distribution of people's movement in space (Hillier , 2004).

This research intends to analyse the changes in movement patterns when ambient displays are used as a virtual extension of the visual boundaries inside public spaces. The hypothesis of this study is that an ambient display able to extend the visual field through a skewed perspective projection towards another space (see Figure 2), which is near but not directly accessible, will influence the topological and visual relations between spaces. As a result it is expected that the distribution of people's movement will be affected.

In contrast to current stable physical spaces, the introduction of new responsive and ever-changing materials will impose new fully adaptive architecture. Therefore, extending current knowledge and theories to involve digital transparencies as a crucial element of spatial configurations is inevitable.

Methodology

To achieve the aims of this research, a series of experiments were developed in order to observe and analyse how the presence of an ambient display and the perspective angle of its projection affect people's movement (see Figure 2). The experiments are focused on the use of ambient displays in the interior of public spaces by placing them near an area of

common interest. Public spaces offer great opportunities for experimenting with ambient technology and the analysis of movement. From a methodological perspective, such places allow observing the movement behaviour of a significant amount of people providing a larger sample for experimentation and analysis.

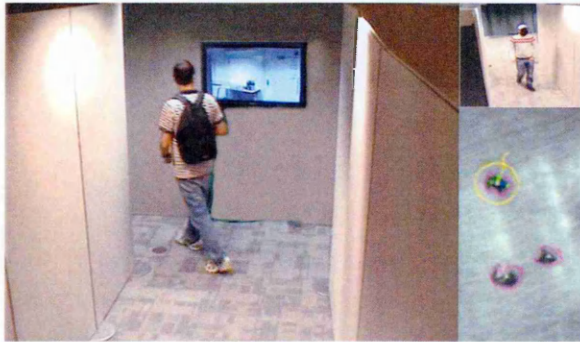


Figure 2
Example of an experiment setting ('left' skewed projection).

A fundamental form of space, in which it is simple to examine the flow and direction of people between discrete routes, is corridor-like settings. Based in this setting, two distinguished routes are needed, from which the users can choose in order to access the target space. 'Target space' is considered as a space with common interest for the participants of the experiment such as a coffee area or a common room that they can prepare and eat their lunch.

This type of experiment gives the opportunity to examine a single 'decision making' point providing clear and unbiased experimental conditions. It is essential that the routes need to be symmetrical in order not to influence the users' choice by producing different visual triggers. Moreover, having the 'T' shaped corridors as the setting, where people can go left or right, gives symmetrical visual characteristics. Therefore, the addition of an ambient display that distort the visual perspective at the wall in front of the end of the corridor as depicted in Figure 3 is expected to act as a visual trigger. The display's presence and the different skewed projections will potentially introduce a digital opening in the visual field and will influence people's movement.

Intuition and a simplistic interpretation of 'Space Syntax' suggest that the presence of an ambient display in a corridor should not influence the route decision-making choices of occupants going down this corridor. In the condition when both routes are equidistant from the objective, one might well expect a 50/50 left-right split of occupants. Alternatively, the hybrid space hypothesis suggests that a digital ambient display that functions like a virtual window, when distorting the visual field with a skewed projection, will alter spatial

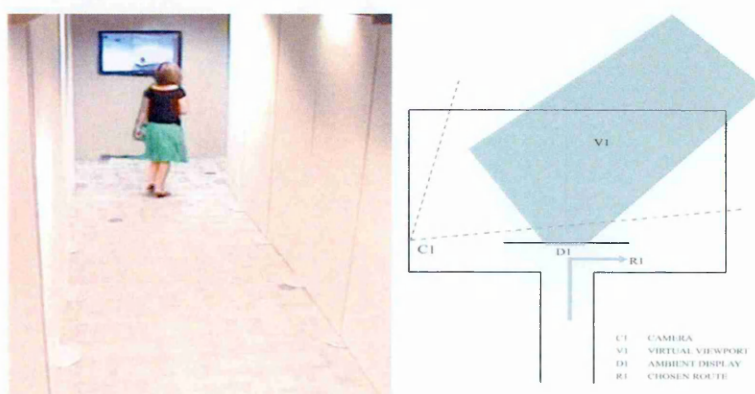


Figure 3
Influencing direction of movement. Experiment setup.

morphology and so will result in an observable behavioural change in movement patterns (see Figure 3). To test this, a set of corridors as a 'T-shaped' arrangement was constructed with the upper part of the 'T' near the target space. As the 'target space', a room for coffee provision was used. The research's interest is to examine how the addition of a skewed perspective view would affect this distribution, a case that currently is not predictable by relevant theories like 'Space Syntax'.

Deriving from the background research and the hypothesis, the display's main function was to act as a live video link providing a one-way video from the 'target space' and introducing an augmented opening that digitally distorts the visual perspective. In addition, a series of 'null-tests' were introduced as part of the experiment using the ambient display with: no content, random static images and random animated content. The 'null-tests' were critical for establishing the content of the display as the only source of influence.

Experimental Set-Up

The space used was the Ambient Technology Lab, an approximately 144 m² area free of internal walls, at the Open University UK. For the construction of the corridor-like setting, full-height lightweight solid partitions were used producing a symmetrical space. The remaining space at the end of the corridor-like setting was designed as a small coffee area, where free coffee, tea and biscuits were available to everyone during the course of the experiment.

For the data gathering, a multi-camera set-up was used for synchronized recording of every

corner of the lab. The cameras were positioned in the ceiling and configured to track multiple angles of the decision-point area as well as the full length of the corridor and coffee area.

The experiment ran over a period of several weeks during working hours and employees and visitors were able to use this setting for taking their morning or afternoon coffee. None of the participants were aware of the research's nature but were informed that they were taking part in an experiment and were being recorded. The experiment area was clearly marked to the effect that they were entering a video monitored zone and emails were sent out to ask for participants. The emails explained that the purpose of the experiment will be revealed after its compilations and the whole process was ethically approved. While participants were asked to use a specific entrance and exit door in order to avoid passing through the corridor in both directions, it was felt that this did not bias participants' response of direction choice.

As discussed before, the measurements had to be compared with a 'base model' of this space with no ambient displays installed. On that account, the experiment started by collecting data about people's movement within the T-shape configuration with no ambient display present. After having sufficient data to serve as the basis of the experiment, the second phase started, in which a large display was carefully embedded into the wall in front of the end (see Figure 3) of the constructed corridor (decision point). The display, a large anti-glare display with a 15 mm black casing, was linked with a high-definition professional camera and depicted the coffee area as seen from a centred 'perspective' in relation to the depicted area. This 'perspective' view was used in order to emulate the actual perspective

of the coffee area that an opening at this position would have revealed. In the third phase the display's placement did not change and a skewed perspective projection was used (off-centre vanishing point) in order to emulate the same effect of a virtual window but as seen from the right side (Figures 2, 3). Similarly, in the forth phase the skewed projection change a symmetrical effect to 'phase 3' but towards the left side. Everything else in the experimental setting remained unchanged for the course of the experiment. At the end of the study all video streams were examined regarding the movement, choice of direction and the reactions of the people. All data were treated with confidentiality and not shared with anyone outside the limits of this research.

In total, more than 900 individuals took part in the experiment, which gives us a clear evaluation of the hypothesis. The number of participants doesn't include people passing multiple times but the observations are kept in order to later check their potential contribution on the overall hypothesis.

Results

To analyse the movement patterns in the experimental setting the number of individuals and groups walking through the corridor were counted in relation to their decision to follow the right or left direction in the particular setting. The data were categorized according to the experimental phase (without display, with the display depicting a centred perspective, with the display depicting a 'right perspective' and with the display depicting a 'left perspective') and whether it was individuals or groups. The analysis conducted by grouping

the data into two categories in order to eliminate any signs of internal influence within the groups of people ('groups' have more than one person and all subjects follow the first person in the group): 1) for 'all groups and individuals' without taking into account if a person was alone or a part of the group and 2) 'only individuals' counting all 'individuals' and each of the 'groups' as one subject unaffected by the number of people in the group. These categories were analysed using a chi-squared test and logistic regression analysis (modelling of binomial proportions).

In the first phase (no display), which took place over a period of four weeks, the findings revealed that combining groups and individuals, 55% of the people turned left in the specific setting and 45% turned right, while counting only the individuals the distribution was 54.8% left and 45.2% right (see Figure 4).

In the second phase where the display produced a centred projection of the 'target area', the distribution was 55.1% turning left and 44.9% turning right for the combined test subjects and 53.7% left and 46.3% right for only the individuals (see Figure 4). Those results showed no significant 'shift', as expected, in people's distribution along the two alternative directions in view of the fact that there was no distortion of the visual field or the 'virtual' spatial topology.

In the third phase where the display produced an off-centred projection with a skewed perspective to the right, the distribution was 37.1% turning left and 62.9% turning right for the combined test subjects and 38.5% left and 61.5% right for only the individuals (see Figure 4). Those results showed a significant 'shift' in people's distribution along the two alternative directions. The shift towards the right side was 17.9% combining all test subjects together and 16.3% counting only the individuals.

Finally, in the forth phase where the display produced an off-centred projection with a skewed perspective to the left, the distribution was 65.3% turning left and 34.6% turning right for the combined test subjects and 65.6% left and 34.4% right for only the individuals. Those results also showed a significant 'shift' in people's distribution (see Figure 4). The shift towards the left side was 10.3% combining all test subjects together and 10.8% when counting only the individuals.

Furthermore, for validation of the significance of the results from the three unmatched groups a chi-square statistical test was used. The p-value of this test was 0.0018.

Following the tests about the general significance of the measured data and the influence of

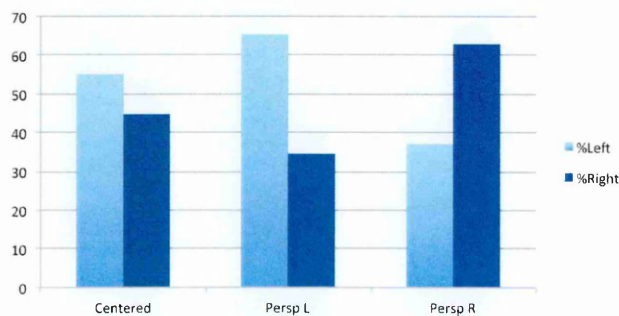


Figure 4
Distribution (%) between routes.

the skewed projections, a logistic regression analysis was conducted ('modelling of binomial proportions'). For this test a value denoting the direction of the skewed projection of the ambient display was introduced (direction of influence): '-1' when the perspective's vanishing point is at the opposite side than the one testing, '0' when there is centred and '1' when the vanishing point is on the same side, as well as a value denoting the presence of an ambient display regardless of projection (encoded as '0' for not present and '1' for present). The 'direction of influence' matches the direction of the significant change in movement as measured in the experiment, with a p-value (t pr.) less than 0.001. The result of this analysis further confirms the hypothesis that the ambient display produces a significant change in the direction of movement, when using skewed projection, towards the side at which the vanishing point of the perspective is located. Additionally, combining the 'direction of influence' and the 'presence' variables evinces that the resulted distortion is not based on the location of the vanishing point (skewed perspective towards right or left), and thus for both 'right' and 'left' cases the change was equally significant.

Null-Tests Results

In relation to the above, there was a need for extracting whether the ambient display itself (the device) or its content were responsible for the findings. For that reason, using the same equipment and spatial setting a follow-up experiment was conducted positioning the display in the same place as the first experiments but without the video link. Instead of the video feed, several scenarios were tested: no image is used in order to test the ambient display as a device while static images, animated images and short video clips used to explore the

effects of diverse content that could affect the users.

The results were treated in the same way as the first experiment and showed that the shift in direction between the phase without a display (base model) and each of the null-test phases is less than 2% in all cases and not statistically significant.

In detail, from more than 350 individuals who took part in the null-test experiments, the majority of people continue to use the left route more (the same way as before the application of the ambient display), with the percentage varying from 56.5% to 53.8% in favour of the left route. What is clearly visible from the results is that the ambient display blends in the environment and becomes an unobtrusive object that without the added visual perspective it does not influence people's behaviour and movement in space.

Conclusion

The results of this study reveal that, an ambient display that shows typical information has, as one might expect, no change on pedestrian route choice behaviour. On the contrary, a non-centred perspective projection of a space influences route choice behaviour towards the side of the projected vanishing point. This has a number of ramifications in terms of both the design of ambient displays in architectural settings and the use of augmented/hybrid spaces in research conditions.

This study also demonstrates that a skewed projection has the effect of increasing awareness about the "target" space giving a subliminal direction towards the side where the

vanishing point of the projection is situated. In some cases the ambient display unconsciously nudged people to pass through the corridor setting and go to the coffee area. As the video revealed, most of the users took decisions quickly. However, there were cases of individuals changing their initial decision and adapting their route towards the side of the 'influence'. It is speculated that raising awareness of this decision may have increased the likelihood that these individuals recalculated the new augmented layout of space against the old and moved accordingly.

Accepting that people's visual perception of space becomes influenced by the virtual augmentation and extension of space that ambient displays produce, this research can contribute in two main areas. One area deals with the architectural space design featuring ambient displays, as well as navigation in space. The second area is the content and interface design for ambient media. In the fast-growing field of digital augmentation in architecture, understanding and acknowledging people's movement, proximity and navigation in space can give new ways of managing and directing movement towards desired places or interfaces. Examples within this area include subliminal nudges for accessibility of remote or 'hidden' spaces as well as alternative and more efficient methods to assist way-finding. In addition, ambient information systems can be made and positioned in a way able to enhance interactivity and social engagement.

The findings of this research enable the need for further analysis and understanding of the fusion between physical and virtual spaces. Exploring in depth the hybrid spaces that emerge through the use of ambient displays will provide more generic insights and allow the effective use of digital augmentation in architecture. Currently, a research that explores the

spatial properties of such hybrid spaces is under development in order to bridge this gap.

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"Reality is merely an illusion, albeit a very persistent one." Albert Einstein